N.A. Rogazin

JET FUELS

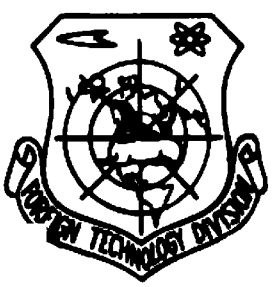
FTD-MT-64-[illegible]

FOREIGN TECHNOLOGY DIVISION

JET FUELS

BY

N. A. Rasorin



This document is a machine translation of Russian text which has been processed by the AN/GSQ-16(XW-2) Machine Translator, owned and operated by the United States Air Force. The machine output has been post-edited to correct for major ambiguities of meaning, words missing from the machine's dictionary, and words out of the context of meaning. The sentence word order has been partially rearranged for readability. The content of this translation does not indicate editorial accuracy, nor does it indicate USAF approval or disapproval of the material translated.

DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

EDITED MACHINE TRANSLATION

JET FUELS

By: N. A. Ragozin

English Pages: 233

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT. STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE FOREIGN TECHNOLOGY DIVISION.

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

N. A. Ragozin

REAKTIVNYE TOPLIVA

Vtoroye Pererabotannoye
i Dopolnennoye Izdaniye

Gosudarstvennoye Nauchno-Tekhnickeskoye Izdatel'stvo
Neftyanoy i Gorno-Toplivnoy Interatury

Moskva – 1963

Pages 1-165

TABLE OF CONTENTS

U. S. Board on Geographic Names Transliteration System..... iii

Designations of the Trigonometric Functions..... iv

Introduction..... 1

1. Sources and Methods of Obtaining Jet Fuels..... 5

2. Carburetion in Gas Turbine Engines..... 10

3. Inflammation and Ionition of Fuel-Air Mixtures..... 16

4. Processes of Burning in Gas-Turbine Engines..... 24

5. Radiant Heat Exchange and Intensity of Radiation of Flame..... 34

6. Heat of Combustion of Jet Fuels..... 40

7. Scale Formation in Gas Turbine Engines..... 54

8. Thermal Stability of Jet Fuels..... 6[illegible]

9. Formation of Tarry Substances in Jet Fuels..... 74

10. Corrosion Aggressiveness of Jet Fuels..... 81

11. Plugging of Aircraft Filters..... 89

12. High-Altitude Characteristics of Jet Fuels..... 95

13. Low-Temperature Properties of Jet Fuels..... 102

14. Cooling of Fuels in Aircraft Tanks..... 108

15. Water Content of Jet Fuels..... 11[illegible]

16. Hygroscopicity of Jet Fuels..... 120

17. Formation of Crystals of Ice in Jet Fuels, Icing and Clogging of Aircraft Filters..... 128

18. Elimination of Crystal Formation in Jet Fuels..... 133

19. Pyrotechnical Characteristics of Jet Fuels..... 137

20. Electrical Properties of Jet Fuels..... 152

21. Storage of Jet Fuels at Airport Storehouses..... 163

22. Fueling of Aircraft..... 168

23. Grades of Jet Fuels of Soviet Union..... 177

24. Grades and Specifications of Jet Fuels of Foreign Countries..... 181

25. Quality of Commercial Grades of Jet Fuels of Foreign Countries..... 193

26. Aviation Gasolines of Foreign Countries..... 200

27. Fuels for Supersonic Flight Speeds..... 208

28. Interchangeability of Jet Fuels..... 213

29. Quality Control of Jet Fuels..... 218

Literature..... 228

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

ANNOTATION

In the book materials are presented on the physicochemical properties and performance characteristics of fuels used for aviation turbojet and turboprop motors in the Soviet Union and in foreign countries.

The book is intended for engineering-technical workers occupied with production and use of jet fuels.

MT-64-292
Jet Fuels, Gostoptekhizdat,
Moscow, 1963.
Pages: Cover-165

INTRODUCTION

In contemporary transport aviation jet engines of different types are widely used, gradually replacing piston motors. On internal and international air lines of Soviet Union high-speed aircraft TU-104 and TU-124 with turbojet engines and aircraft IL-18, AN-10, AN-24 and TU-114 with turboprop motors are in operation. In the near future on long distance air lines there will appear a new type of high-speed aircraft, IL-62 with gas-turbine engines.

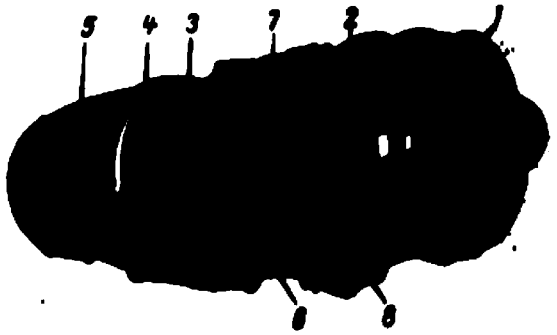
Already now on all main (internal and international) air lines of the Soviet Union chiefly high-speed aircraft with gas-turbine engines are in operation.

Turbojet Engines

In a turbojet engine (Fig. 1) the air is compressed in mechanical compressor set in motion from gas turbine. Dynamic compression of air in turbojet engines occurs during flight because of impact pressure. But at subsonic flight speeds this compression does not have great value.

In gas turbine of turbojet engines only part of pressure drop of gases is used, while the work developed by turbine is completely expended on drive of air compressor and accessories of motor. The

main part of pressure drop is used in jet nozzle for increase of kinetic energy of gases, which, flowing from jet nozzle, create tractive force.



GRAPHICS NOT REPRODUCIBLE

Fig. 1. Appearance of turbojet engine. 1) discharge part of motor; 2) body of compressor; 3) body of ring chamber; 4) body of gas turbine; 5) jet nozzle; 6) oil tank; 7) fuel-oil radiator; 8) right box of drives of accessories with oil pumps and filter.

Specific expenditure of fuel in different types of turbojet engines is different and in the most contemporary of them amounts to 0.7-0.8 kg/kg.

Turboprop Motors

Turboprop motors in their arrangement are very similar to turbojet engines. Main distinction between them consists of the fact that in turboprop motors expansion of gases occurs almost completely in gas turbine, thanks to which power of turbine significantly exceeds the power required for drive of air compressor and accessories, and surplus power is transmitted to propeller (Fig. 2).

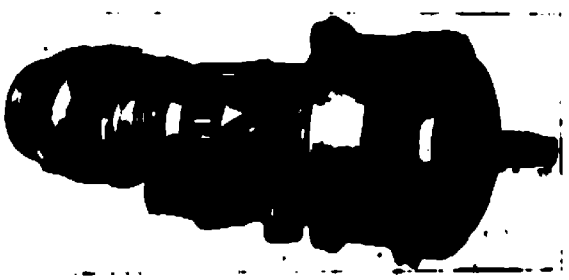


Fig. 2. Appearance of turboprop motor.

Jet traction, created by outgoing gases, in turboprop motors is obtained because of the use of discharge velocity of turbine and amounts to only 10-20% of entire traction of installation.

Specific consumption of fuels in turboprop motors of different types oscillates within limits of 200-250 g/hp·hr.

In development of high-speed transport aviation an exceptionally important role belongs to fuels. High quality of jet propellants and their correct use in significant measure determine reliability and effectiveness of work of gas-turbine engines and flight safety of high-speed aircraft. Means expended on propellants amount to around 30% of operational expenditures of jet transport aviation.

1. SOURCES AND METHODS OF OBTAINING JET FUELS

Main source of obtaining propellants is crude — a combustible oily liquid, more frequently dark, but sometimes a light yellow color. It consists of a mixture of liquid hydrocarbons, in which in small amount are dissolved gaseous and solid hydrocarbons. Besides hydrocarbons, in oil in small amount are contained oxygen, sulfur and nitrogen compounds and some other substances.

Average elementary composition of crude is the following: carbon 86%, hydrogen 13%, sulfur and nitrogen 1%. Density of crude oscillates from 0.730 to 1.00 g/cm^3. Viscosity of crude is different. Crude can be from very fluid to very viscous. Heat of burning of oil oscillates within limits of 10,300-10,900 kcal/kg.

Methods of Production of Jet Fuels

Majority of kinds of propellants if obtained from crude by method of direct distillation. This method consists in the fact that oil will be divided into separate fractions (parts) according to boiling point. For separation into fractions crude is heated in special tubular furnaces, and from there fed by pump into fractionating column, where it is fractionated, i.e., divided into fractions according to the boiling point. As a result of such distillation, from crude can be obtained gasoline, kerosene and gas-oil fraction,

from which after their additional processing commercial products are obtained, aviation gasoline or automobile, aviation kerosene, diesel fuel and others.

In crudes of different deposits the content of separate fractions is different. In some crudes gasoline and kerosene fractions are contained in large quantity, in others little of these fractions is contained.

Fuels obtained from crudes of different deposits by method of direct distillation have different chemical composition, and due to this the physicochemical characteristics of fuels will also be unequal. Thus, kerosene fraction, evaporating within limits of 120-280°C, obtained from crudes of naphthenic base, has temperature of beginning of crystallization of -60°C, and such a fraction, obtained from crudes of paraffin base, -40°C and higher.

Thus, it is not possible to obtain aviation kerosenes of type T-1, having temperature of beginning of crystallization of -60°C from all oils. From some crudes for obtaining of aviation kerosene with crystallization temperature of -60°C it is necessary to remove lighter kerosene fraction. Thus, so that aviation kerosene of type TS-1, obtained from sulfurous Volga crudes, had temperature of beginning of crystallization not higher than -60°C, the temperature of its termination of boiling should not be higher than 250°C.

From listed examples it is clear that kerosene fractions, used as fuel for gas-turbine engines evaporate in narrow limits; therefore yields of such fractions from oil are comparatively small.

In connection with the fact that consumption of jet propellants in recent years has been growing extraordinarily fast, in certain countries there appeared fine problem of sharp increase of production

of jet propellants. Experience of recent years showed that such a problem can be solved in two ways:

1) increase of yields of fuel from crude because of expansion of fractional composition of jet propellant (Table 1);

2) inclusion in composition of fuel of not only products of direct distillation of crude, but also products of catalytic cracking.

For the purpose of expansion of production of jet fuels in present military aviation of the United States and England fuels of wide fractional composition, evaporating within limits of 60-280°C are widely used. This is no longer a narrow kerosene fraction, but a wide fraction, into whose composition enters gasoline, ligroin and kerosene.

From the same crude by method of direct distillation can be obtained fuels of wide fractional composition (T-2), almost two times larger than fuels of type of aviation kerosenes (T-1) [1] (Table 1).

Table 1. Dependence of Freezing Point of Fuel on Yield of Fraction from Crude

Fuel	Freezing point	Yield of fuel on crude, % weight
Aviation kerosene (type T-1).....	-40	25
The same.....	-60	10
Wide fraction (type T-2).....	-40	50
The same.....	-60	35

Group Chemical Composition of Jet Fuels

All sorts of propellants obtained from crude consist of hydrocarbons, which are divided into the following four groups: paraffin, naphthenic, aromatic and unsaturated. In jet propellants

obtained from various oils the content of different groups of hydrocarbons is not identical and depends on the type of crude from which the fuel was obtained. Thus in kerosene fraction evaporating within limits of 122-300°C and obtained from Emba crude, the content of naphthenic hydrocarbons oscillates from 62.7 to 91.4%. In the same kerosene fraction, evaporating within limits of 122-300°, obtained from Grozny oil, content of naphthenic hydrocarbons amounts to 20.49-33.44% [2].

Group chemical composition of commercial kinds of jet propellants is listed in Table 2.

Table 2. Group Chemical Composition of Jet Propellants

Fuel	Content of hydrocarbons in fuels, %			
	Unsaturated	Aromatic	Naphthenic	Paraffin
T-2.....	0.10-0.30	15.10-11.4	18.80-29.30	66.0-59.0
TS-1.....	0.7-1.0	16.2-15.4	24.4-21.4	58.7-62.2
T-1.....	0.4-0.5	14.3-15.6	34.6-52.4	50.7-32.0
T-5.....	0.6	18.9	57.2	23.3
"ATK" (England).	0.2	14.5	34.2	51.1
JP-4 (Sweden)...	0.3	15.4	27.6	56.7

Experiments showed that from the point of view of requirements presented to jet propellants, different groups of hydrocarbons entering into the composition of kerosene fraction, are far from equivalent. The most desirable groups of hydrocarbons are paraffin and naphthenic. Hydrocarbons of these two groups have great heat of combustion, possess high chemical stability, during prolonged storage are not oxidized and during combustion in motor give little deposit. Aromatic hydrocarbons for jet propellants are considered less desirable, since their heat of combustion per unit of weight is almost 10% lower than heat of combustion of paraffin hydrocarbons.

During combustion of aromatic hydrocarbons heightened deposit formation in motor is observed. Furthermore, aromatic hydrocarbons possess high hygroscopicity. Finally, they can render harmful destructive action on soft rubberized tanks used on certain types of jet transport aircraft.

In connection with the indicated existing specifications jet propellants not more than 20-25% of aromatic hydrocarbons is allowed.

Presence of unsaturated hydrocarbons in jet propellants is undesirable. In fuels of foreign countries not more than 5% of unsaturated hydrocarbons is allowed, but with native [Soviet] specification for fuels T-1, TS-1 and T-2 iodine number of fuel not more than 2-3.5 is allowed, which corresponds to 1-2% of unsaturated hydrocarbons.

Strict limitation of content of unsaturated hydrocarbons in jet propellants is explained by low chemical stability of these hydrocarbons.

2. CARBURETION IN GAS TURBINE ENGINES

To guarantee effective evaporation of liquid fuel fed into combustion chambers of gas-turbine engines, fuel should be well atomized. Mechanism of atomization of fuel up to now was insufficiently studied, and there is no general theory on the basis of which it would have been possible to predetermine the necessary fineness of atomization of fuels. General character of process of atomization of fuels usually is established according to results of numerous experimental works and some theoretical positions.

Process of atomization of liquid fuel can be conditionally subdivided into the following stage:

1) formation of shroud or stream of fuel as a result of flow of liquid through burner;

2) appearance of small ripple and perturbations on surface of liquid due to initial turbulence of liquid and influence of air on liquid stream;

3) formation of thin films of liquid under the action of air pressure and forces of surface tension;

4) breaking down of films into separate drops because of the surface tension of fuel;

5) further, finer breaking down of these drops.

Atomization of fuel is carried out by injection of it at high speeds into relatively motionless air (atomization by pressure), or by means of influence of high-speed air flow on stream of fuel flowing at relatively low speed (air atomization), or by a combination of both these methods.

Disintegration and breaking down of films into separate drops during atomization is influenced by the magnitude of surface tension of fuel. Films separated from main mass of liquid stream of fuel and due to instability are broken up into great number of small drops. With this at higher speeds of stream thinner films are formed, disintegrating into smaller drops.

It was established that films of fuels with high surface tension are destroyed faster; therefore bigger drops of fuel are formed.

Surface Tension of Jet Fuels

Magnitude of surface tension depends on physicochemical properties of fuels. Significant influence on magnitude of surface tension of fuels is temperature; the higher the temperature, the lower the surface tension of fuels.

Surface tension is a large influence on process of atomization of fuel by burner. It is accepted to consider that, other things being equal, magnitude of drops of fuel during injection is inversely proportional to magnitude of surface tension of fuel.

Surface tension of different sorts of fuels at different temperatures is given in Table 3.

Table 3. Surface Tension of Jet Propellants (in ergs/cm^2) Depending on Temperature [3]

Temperature °C	B-70	T-1	T-5	Temperature °C	B-70	T-1	T-5
-50	29	33	34	50	19	24	25
-20	26	30	31	100	14	19	21
0	24	28	29	150	10	15	17
20	22	26	27	200	6	11	14

Diffusion of Fuel Vapors in Air

During evaporation of drops of atomized fuel continuous process of formation of vapors proceeds. Formed fuel vapors strive far equal distribution through the entire volume of air.

Diffusion rate (penetration) of fuel vapors in air is expressed by coefficient of diffusion. With increase of temperature of fuel vapors their diffusion rate is increased.

Dependence of diffusion coefficient of vapors of jet fuel T-5 on temperature [3] is characterized by the following data:

Temperature °C	Diffusion coefficient 760 mm Hg cm^2/sec	Temperature °C	Diffusion coefficient 760 mm Hg cm^2/sec
0	0.0287	330	0.1356
250	0.1026	350	0.1446
270	0.1104	370	0.1538
290	0.1184	390	0.1633
310	0.1269	400	0.1683

Viscosity of Fuel

Viscosity of individual hydrocarbons under constant external conditions – is constant magnitude and is their physical characteristic.

Viscosity of jet propellants representing a physical mixture of hydrocarbons depends on chemical composition of hydrocarbons entering into fuel.

Viscosity of fuel is significant influence on work of pumps and on atomization of stream of fuel by burner. The lower the viscosity of jet propellant, the easier the stream breaks up under the influence of appearing centrifugal forces, the better it is atomized and the smaller the drops of fuel. Consequently, specific surface of evaporation (cm^2/cm^3) and evaporation rate will be inversely proportional to viscosity of fuel.

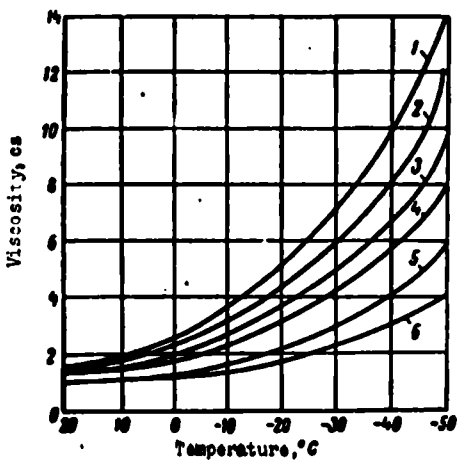


Fig. 3. Dependence of viscosity of jet propellants on temperature. 1) fuel T-1; 2) Danish fuel ATK; 3) English fuel ATK; 4) fuel TS-1; 5) fuel T-2; 6) Swedish fuel JP-4.

However, in experimental works it is very difficult to grasp the influence of small change of viscosity of fuels, since change of other physical propellant properties accompanying the change of viscosity (surface tension etc) camouflages the influence of viscosity on atomization and evaporation of fuel.

With increase of temperature the viscosity of fuel drops (Fig. 3), while this change of viscosity is so significant that it is a great influence on atomization (breaking down) of stream in flow of air by burner.

Starting Properties of Jet Fuels

As starting properties of jet propellants it is conditionally acceptable to consider ease of ignition of fuel-air mixture in combustion chamber of gas-turbine engines. As index of starting qualities of jet propellants most frequently is taken the necessary minimum pressure of fuel in front of the burner at which stable ignition of fuel-air mixture of given type of fuel is achieved.

Research established that ease of ignition of fuel-air mixture depends on construction of engine and its starting devices (power and construction of source of ignition, place of its location, etc), and also on properties of fuel.

Starting properties of fuels depend mainly on physical properties of fuel and in the first place on those which affect processes of evaporation and carburetion. The most important of these characteristics are: pressure of saturated vapors, boiling away of 10% and viscosity.

In Table 4 are listed starting properties of different types of jet propellants [5].

Table 4. Starting Properties of Jet Propellants

Fuel	Pressure of vapors at 38°C, mm Hg	Evaporates 10%, °C	Viscosity at 20°C, cs	Pressure of fuel in front of burner, kg/cm²
Aviation gasoline B-70...	250	82	0.69	3.0
Isooctane.....	115	96	0.71	3.5
Fuel T-2.....	100	127	1.05	5.0
Fuel TS-1.....	50	153	1.25	8.0
Fuel T-1.....	40	162	1.73	9.5
Fuel T-5.....	26	183	3.68	11.5

*Ensuring easy inflammation. [There is no asterisk in the table to which this remark specifically corresponds [Tr. Ed. note].]

From Table 4 it is clear that fuels of light fractional composition possess the best starting properties.

3. INFLAMMATION AND IGNITION OF FUEL-AIR MIXTURES

Source of ignition of flow of fuel-air mixture proceeding through combustion chamber of gas-turbine engine can be electrical spark, open flame and, finally, heated metallic surface.

It is known that the temperature of inflammation and ignition of motionless fuel-air mixture (according to method of a drop) for jet propellants lies within limits of 220-250°C.

Temperature of inflammation of flow of fuel-air mixture is 4-5 times higher than temperature of inflammation of motionless mixture. Experiments established that the higher the rate of flow, the higher the temperature which is able to cause ignition of mixture (Table 6). Dependence of temperature of ignition of fuel-air mixture of stoichiometric composition in flow (pentane – air) on speed is given below.

Rate of fuel-air flow, m/sec	30.0	37.5	45.0	52.5	60.0
Temperature of surface of metallic rod causing ignition of mixture °C	1140	1150	1170	1230	1311

Ignition of Spray Fuel in Mixture with Air

Works of recent years established that finely atomized fuel (spray) can form with air inflammable mixtures whose limits of

inflammation are almost identical with limits of inflammation of mixtures of vapors of this fuel with air.

In Table 5 are listed data [6] showing limits of inflammation of mixtures of vapors and small drops (10 μ) with air.

Table 5. Limits of Inflammation of Mixtures of Vapors and Small Drops with Air

Composition of mixture	Limits of inflammation (ratio of fuel to air)	
	Lean mixture	Rich mixture
Vapors of fuel JP-1 with air.....	0.037	0.310
Spray fuel JP-1 (drops 10 μ) with air.....	0.043	0.230

If we consider that limits of inflammation of vapors were determined at 149°C, and limits of inflammation of sprays (drops) at 0°C, then in both cases limits of inflammation are practically identical.

Works were conducted on clarification of influence of diameter of drops of fuel on limits of inflammation of sprays of lean mixtures. In this work as fuel was taken tetralin, and dimensions of drops of fuel in air oscillate from 7 to 50 μ. Results of conducted research are given below.

Diameter of drops in spray, μ..	7	15	25	30	40	50
Ratio of fuel to air at lean limit of inflammation.....	0.039	0.032	0.026	0.021	0.016	0.014

From the given data it is clear that the limit of inflammation of fuel-air mixtures for small drops corresponds to ratio of fuel to air of 0.039, which approximately equals the ratio of vapor air mixtures. With increase of dimension of drops of fuel the limit of inflammation of lean mixture drops. At the same time depending on

dimensions of drops structure of flame is also changed. In the case of small drops of fuel the flame has the form of usual flame of lean mixtures, but with increase of dimension of drops the flame is broken up even more into separate areas of burning around separate drops.

Research established that with identical concentration of fuel in air, rates of flame propagation in fuel-air mixture and in spray are approximately identical (Table 6).

Table 6. Rate of Flame Propagation in Spray and Vapors

Fuel	Ratio of fuel to air	Fuel in the form of spray		Fuel in vapor state	
		Temperature, °C	Speed of flame, m/sec	Temperature, °C	Speed of flame, m/sec
Kerosene fraction (180-220°C).....	0.044	24	1.1	60	1.3
	0.061	34	4.9	60	5.5
	0.072	37	5.8	60	6.7
Tetralin.....	0.040	29	0.7	100	0.79
	0.080	45	1.1	100	1.9

Ignition of Fuel-Air Mixtures at Low Pressure

Possibility of ignition of fuel-air mixtures and propagation in them of flame at low pressures are connected with creation of stable burning of fuels in combustion chamber and with problem of repeated starting of gas-turbine engine during flights of aircraft at a great altitude.

Importance of these factors for high-speed combustion chambers is completely evident, since in operation such conditions can be created, with which fuel-air mixture will not inflame, and even if it does inflame, then it will not ensure stable burning.

For different types of fuels various minimum pressures exist at which ignition of fuel-air mixtures is possible [7, 6].

Fuel	Minimum pressure of ignition, mm Hg
Aviation gasoline 100/130.....	16.0
Aviation gasoline 115/145.....	38.1
Fuel JP-3.....	38.1
Fuel JP-4.....	12.95
Methane.....	19.05
n-Butane.....	28.96
Benzene.....	27.94
n-Nonane.....	33.02

These data were obtained during ignition with condensed spark of commercial types of fuels at 25.6°C and distance between electrodes of 2.54 mm, and also of individual hydrocarbons at 24-29.5°C and distance between electrodes of 2.8 mm.

In NASA laboratory analogous investigations were conducted on study of limits of flame propagation in fuel-air mixtures at low pressures. These experiments were conducted in tube 50 mm in diameter; as source of ignition an incandescent wire was used.

It was established that limits of flame propagation both through lean and also through rich mixtures actually are not changed with decrease of pressure from 760 to 250 mm Hg. With further lowering of pressure extinguishing influence of walls of tube shows, and therefore fast approach of limits of flame propagation through lean and rich mixtures occurs. Finally, at certain minimum pressure below which flame cannot spread in uniform mixtures in tube with diameter of 50 mm, the limits coincide.

Limits of flame propagation in fuel-air mixture of jet propellant JP-3 depending on pressure are given in Table 7.

Table 7. Limits of Inflammation of Fuel-Air Mixtures Depending on Pressure [8]

Pressure, mm Hg	Content of fuel vapors in air, volume %	
	Lean mixtures	Rich mixtures
50	1.75	7.50
100	1.50	7.75
200	1.35	7.75
300	1.25	7.50
400	1.25	7.75
500	1.35	7.75
600	1.40	7.75
700	1.50	7.70
740	1.50	7.70

From data of the table it is clear that concentration limits of stable flame propagation in mixture of vapors of jet propellant JP-3 and air with lowering of pressure are somewhat narrowed, but this narrowing is very insignificant.

Critical Distances

Inflammable mixture usually is considered a mixture in which flame can spread without limit from source of ignition. Sometimes it is possible to observe how stable flame in mixture occurring within the limits of inflammation dies out with passage of narrowed space. Obviously, walls can render a certain negative influence on the flame. Such an influence of walls on flame propagation is called extinguishing action of walls. Minimum diameter or minimum dimensions of rectangular aperture through which flame can still pass, is called the critical distance, or distance of extinguishing [9].

Below are listed values of critical distances for different hydrocarbons (experiments were conducted at atmospheric pressure and temperature of air on outlet of 100°C; mixture took stoichiometric composition).

Benzene.....1.70 mm
Propane.....1.87 mm
n-Heptane.....1.95 mm
Isooctane.....2.13 mm

Experiments established that with increase of temperature of mixture the critical distance decreases, and with decrease of pressure the critical distance is increased (Table 8).

Table 8. Influence of Temperature and Pressure on Critical Distance During Burning of Propane-Air Mixture of Stoichiometric Composition [9]

Influence of temperature, pressure of 737 mm Hg		Influence of pressure, temperature of 25°C	
Temperature of mixture, °C	Critical distance, mm	Pressure, mm Hg	Critical distance, mm
27	1.45	760	1.80
127	1.55	273	4.90
210	1.87	101	11.25
285	2.10	63	18.0

Starting of Gas-Turbine Engine in Flight

With climb of aircraft in altitude when external atmospheric pressure is lowered, the dependence of limits of stable burning on composition of mixture is significantly increased. Accidental sharp enrichment or impoverishment of mixture during change of adjustment of engine or flight conditions may cause flameout and spontaneous turning off of engine. For starting of stopped motor in flight it is necessary that electric discharge ensures inflammation of fuel in starting mechanism and the hot gases formed with this ensure evaporation and inflammation of working fuel in flow.

During flights at a great altitude and at very low pressure of atmospheric air, burning of priming fuel proceeds usually sluggishly and with this so little heat is liberated that it is insufficient for ignition of flow of fuel-air mixture passing through combustion chamber. Therefore for repeated starting of engine in flight the aircraft is forced to lower itself usually to such a height at which such a starting is easily ensured.

However losses of altitude due to great expenditures of time on starting of gas-turbine engine is not always acceptable, and sometimes it is dangerous (military aviation).

For facilitation of starting of gas-turbine engines at a great altitude in recent years works were conducted on creation of special priming fuels, which are capable of self-inflammation and energetically burn at very low pressure. In the United States [10] experiments are being conducted on the use for this purpose of metal-organic compounds — trimethyl aluminum and triethyl aluminum. Mixture of these compounds easily spontaneously inflames in air and during combustion liberates such a quantity of heat which ensures ignition of flow of fuel-air mixture at an altitude up to 16000 m.

Table 9. Influence of Addition on Inflammation of Kerosene

Ratio of air to fuel	Maximum altitude at which inflammation of fuel-air mixture is possible, m	
	Aviation kerosene	Aviation kerosene +3% addition $AL(BH_4)_3$
40	12700	14500
50	11200	13100
60	10500	12500

In literature [11] there are data showing the dependence of stable inflammation and consequently also of starting of engine on composition of mixture and air pressure (altitude of flight).

In Table 9 are listed data about influence of addition of 3% $AL(BH_4)_3$ on inflammation of aviation kerosene ATK.

Period of Delay of Inflammation (Ignition)

Period of delay of inflammation (ignition) of fuel-air mixture is called the interval of time between the moment of supply of mixture to source of ignition (for instance, heated plate) and the moment of appearance of first criteria of ignition (inflammation).

Depending on conditions of ignition for the same kind of fuel the period of delay of inflammation can be different. In Table 10 are listed values of period of delay of inflammation of stream of aviation kerosene ATK with average diameter of drops according to Sauter of approximately 100 μ depending on temperature and pressure of air flow.

Table 10. Delay of Inflammation During Injection of Aviation Kerosene into Heated Air [58]

Temperature of heated air, °C	Delay of inflammation in sec with air pressure, mm Hg			
	251	365	654	760
1010	0.003	0.002	0.0012	0.0009
940	0.007	0.0055	0.0035	0.0025
878	0.020	0.015	0.009	0.007
824	—	—	0.025	0.020

From the table it is clear that with lowering of temperature and pressure the period of delay of inflammation of aviation kerosene increases.

4. PROCESSES OF BURNING IN GAS-TURBINE ENGINES

Process of burning in gas-turbine engines proceeds with large surplus of air and at high speeds of air flow in the combustion chamber.

High coefficient of surplus of air in these engines is used for limitation of temperature of gases entering the gas turbine. In contemporary gas-turbine engines the maximum permissible temperature of gases in front of the turbine is considered 1150-1250°K. To maintain such a temperature of gases in front of the turbine it is necessary that general coefficient of surplus of air is of the order of 3.8-4.0. However with strong impoverishment the fuel-air mixture inflames with difficulty, and its combustion proceeds sluggishly and unstably. Even in the case when the mixture inflames, flame jet is not kept in the combustion chamber, and is easily torn off by flow of fast flowing air, and process of combustion is disturbed.

Therefore in gas-turbine engines air proceeding from the compressor is divided into two parts. Smaller part of air, called the primary air, heads directly to the zone of burning, which occupies the front part of chamber and ensures combustion of the main part of the fuel fed through the burner into the chamber. Quantity of primary air amounts to 20-30% of total consumption of air and is established

from such a calculation, so that in zone of burning the coefficient of surplus of air was near to unity. Temperature in zone of burning usually reaches 1800-2100°K, in consequence of which with good atomization of fuel and well organized process of carburetion favorable conditions are created for intense burning of fuel and obtaining of short and stable flame.

Larger part of air (70-80%), the so-called secondary air, flows outside the front part of firebox and, passing the zone of burning, is admixed with products of combustion, diluting them and lowering the temperature of gases entering the gas turbine.

In zone of mixing of secondary air with hot gases along with lowering and levelling of temperature of gas there occurs burning of fuel and products of its incomplete oxidation, if they are carried by flow from the main zone of burning. It was determined that flame jet formed in the zone of burning will be stable only if the speed of flame propagation is not less than the stream velocity of air. Otherwise flame breaks off and stable burning becomes impossible.

Division of air into two parts and enrichment of mixture in the main zone of burning up to coefficient of surplus of air, close to unity, promotes increase of speed of flame propagation. However, even under this condition the speed of flame propagation remains sometimes lower than speed of flow of air on getting out of the compressor. For creation of stable burning, as a rule, the whole flow of air on entering the combustion chamber is braked to speed of the order of 30-60 m/sec by means of increase of passage section. With this primary air with the help of special flame-holding screen is braked to speed not exceeding in the zone of burning 15-25 m/sec.

Beyond flame-holding screen is created a region of stagnation with return-vortex flows of air and hot gases. Vortex movement of air

beyond the screen ensures penetration of air inside the zone of burning and promotes good mixing of it with atomized fuel, and return vortex flows of hot gases — igniting (inflammation) of fresh mixture and its stable combustion.

Amount of Air Necessary for Combustion

Amount of air necessary for complete combustion of fuel can be calculated on the basis of its elementary chemical composition. For the majority of kinds of jet propellants obtained from crude, the amount of air necessary for combustion of 1 kg of fuel oscillates within limits of 14-15 kg (Table 11). There exists a general rule; with loading of fractional composition of fuel there is observed a certain increase of ratio C:H, and due to this the amount of air necessary for complete combustion decreases. With accuracy sufficient for practical purposes the amount of air necessary for complete combustion can be calculated according to the formula

$$G = \frac{2.67\,C + 8H - O}{0.232},$$

where G is the amount of air necessary for burning in kg; C is the content of carbon in fuel in %; H is the content of hydrogen in fuel in %; O is the content of oxygen in fuel in %; 0.232 per weight is the share of oxygen in air.

Table 11. Elementary Composition of Fuel and Necessary Amount of Air for Burning

Fuel	Elementary composition of fuel, average %		Theoretically necessary amount of air for combustion, kg/kg
	C	H	
T-1.....	88.0	12.0	14.6
TS-1.....	85.6	14.4	14.7
T-2.....	85.3	14.7	14.9
Aviation gasoline B-95/130.....	84.5	15.5	15.0

Elementary Composition of Jet Fuel

Jet Propellants consist practically completely of hydrocarbons. Content of other elements, for instance, sulfur, nitrogen, oxygen and so forth, as a rule, does not exceed fractions of a percent. Due to this, for practical calculation it is possible to consider that jet propellants consist only of two elements (carbon and hydrogen), and the insignificant content of sulfur, nitrogen and oxygen is not taken into account.

There exist sufficiently accurate methods of experimental determination of the elementary composition of fuels by means of burning a weighed protion of fuel and catching the products of combustion. However the elementary composition of fuel with some approximation can be calculated also with the help of the following empirical formula [30]:

$$H\% = 26 - 15\rho^{15}; \quad C\% = 100 - (26 - 15\rho^{15}),$$

where ρ^{15} is the density of fuel at 15°C.

Propagation of Front of Flame in Gas Flow

Burning rate, more correctly the speed of propagation of front of flame during burning of fuel-air mixture in gas flow, depends [12] on the content of fuel in air and on the rate of flow of gases in combustion chamber (tube). In experiments during burning in tube with diameter of 141 mm the maximum speed of flame propagation was observed with content of fuel vapors in air of 2.0-2.5% (Fig. 4). As can be seen from the figure, the speed of flow of gases render a strong influence on the speed of propagation of front of flame.

Conditions of Stable Burning

As is known, main purpose of combustion chamber in gas-turbine engine is effective transformation of chemical energy contained in

fuel into thermal, and then into kinetic energy of gases going out of the jet nozzle. This transformation should be effective not only in respect to completeness of reaction of burning, but also from the point of view of aerodynamics.

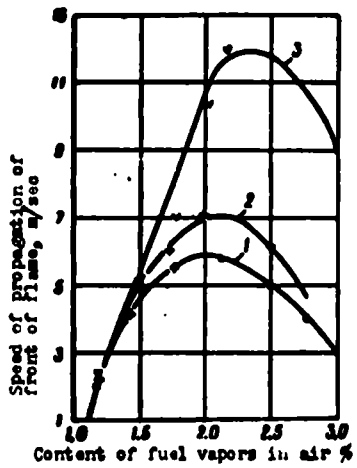


Fig. 4. Speed of propagation of front of flame at high speeds of flow in tube, d = 141 mm. Speed of flow of gases: 1-11 m/sec; 2-20 m/sec; 3-37 m/sec.

Importance of aerodynamic processes for burning appears still greater during burning of vapors of finely atomized stream of liquid fuel (spray), well mixed with air. At speeds of flow exceeding the speed of propagation of laminar flame (for majority of hydrocarbons amounting to approximately 0.3-0.6 m/sec), uniform mixture does not inflame and will not form stable front of flame if structure of aerodynamic flow is such that in flow there are not created local vortexes and zones of reverse current. Consequently, in order to stabilize flame at the high speeds met in jet engines, it is necessary to create zones of movement of flow at low speeds, at which flame or aerodynamic flow of such structure can appear with which local vortexes or reverse currents can be formed.

Limits of Stable Burning in Gas-Turbine Motors

High stability of burning of fuel-air mixture is the most important operational characteristic of gas-turbine engines.

Stable burning is considered such with which stable combustion without breakdown of flame and without torch on outlet of combustion chambers is observed.

With the same construction of combustion chamber the strongest influences on stability of combustion of fuel-air mixture are: air pressure (altitude of flight), temperature of external air, engine revolutions, etc. Experiments established the lower the atmospheric pressure (i.e., the greater the altitude of the flight), the less stable is the burning. Stability of burning is disturbed with small number of engine revolutions, especially at low temperatures of surrounding air.

The most important physicochemical properties of fuels, which influence the stability of burning during impoverishment of mixture, are fractional composition (boiling away of 50%), vapor pressure and viscosity, i.e., characteristics influencing the process of carburetion (Table 12).

Table 12. Limit of Stable Burning of Jet Fuels (5)

Fuel	Vapor pressure at 38°C, mm Hg	Temperature of boiling away of 50%, °C	Viscosity at 20°C, cs	Coefficient of surplus of air α, corresponding to flameout during impoverishment of mixture	Coefficient of surplus of air α, corresponding to appearance of torch on outlet of combustion chamber
Isooctane.....	115	97	0.71	17.2	3.31
Aviation gasoline B-70..	250	102	0.69	16.8	3.44
Benzene.....	176	78	0.74	16.9	4.92
Fuel T-2.....	100	165	1.05	14.4	3.63
Fuel TS-1.....	50	176	1.25	11.9	3.63
Fuel T-1.....	46	196	1.73	10.6	3.82
Fuel T-5.....	26	261	3.68	9.3	3.90

The limits of stable burning during enrichment of fuel-air mixture (appearance of flame jet on outlet of chamber) are noticeably influenced by the chemical composition of fuel. As a rule, during burning in gas-turbine engines fuels with large content of aromatic

hydrocarbons form torch of burning of greater length than fuel of paraffin-naphthenic base not containing aromatic hydrocarbons.

Completeness of Combustion of Fuels in Gas-Turbine Engine

Completeness of combustion of jet propellant is a very important operational characteristic of it and is determined mainly by construction of combustion chamber of engine and by physicochemical properties of fuel.

During test on land the completeness of combustion of fuel in gas-turbine engines reaches 98%. During flights at a great altitude, at lowered pressures in combustion chamber and low air temperatures it significantly decreases, and the influence of propellant properties noticeably increases. Completeness of combustion of fuel in gas-turbine engines in significant measure is determined by its fractional composition and by other properties influencing processes of carburetion (vapor pressure, viscosity, etc).

During test in the same combustion chamber a clearly expressed dependence is observed: the lighter the fractional composition, the higher the pressure of saturated vapors and the lower the viscosity of fuel, the higher the completeness of combustion (Table 13).

Table 13. Completeness of Combustion of Jet Propellants[5]

Coefficient of surplus of air, α	Completeness of combustion of different kinds of fuels, % (during testing on one-chamber installation on land)				
	B-70	T-2	TS-1	T-1	Diesel fuel
3	92	91	90	89	85
4	95	93	92	90	86
5	94	90	90	85	65
6	92	87	83	77	48
7	86	78	70	63	32

Influence of Water Vapor on Flame Propagation

Water vapor has accelerating influence on flame propagation during burning of carbon monoxide and weak retarding action during burning of hydrocarbons.

Thus, during burning of butane-air mixture containing 2.8% of water vapors by volume, speed of flame propagation was 8-10% lower than during burning of analogous mixture containing 0.08% water vapor.

Composition of Products of Burning of Jet Fuel

Composition of undissociated products of burning of jet propellant of type of aviation kerosenes changes depending on the composition of mixture. With impoverishment of composition of mixture, the content of excess oxygen is increased and the amount of final products of oxidation CO_2 and H_2O correspondingly decreases (Table 14).

Table 14. Dependence of Composition of Products of Burning of Aviation Kerosene on Composition of Mixture

Gases	Composition of products of burning of aviation kerosene, %			
	$\alpha = 1.0$	$\alpha = 1.25$	$\alpha = 1.5$	$\alpha = 2.0$
CO_2.....	19.65	15.92	13.38	10.14
H_2O.....	8.38	6.79	5.71	4.33
O_2.....	0	4.40	7.40	11.22
N_2.....	71.97	72.89	73.51	74.31

Injection of Water or Water-Methanol Mixture into Gas-Turbine Engines

For the purpose of keeping or increasing the power of gas-turbine engine on takeoff, which is especially important during work in hot

and tropic conditions, in some cases injection of water or water-methanol mixtures into engine is made.

In practice two methods of injection of water are used: a) into the zone of air inlet; b) directly into the combustion chamber of gas-turbine engines. During injection of water or water-methanol mixture into zone of air inlet (cooling injection), lowering of temperature of air is achieved and increase of its density because of heat removal for evaporation of injected liquid. In this case with any given turns larger per weight amount of air proceeds into compressor; consequently higher power of motors can be obtained. Injection of water or water-methanol mixture into combustion chambers is considered structurally simpler; with this lowering of temperature of burning (gases) is achieved, which allows us to burn larger amount of fuel at the same permissible temperature of gases in front of the turbine. Energy increased thus can be transmitted to turbine, and used for increase of traction of turbojet engine or for increase of power on shaft of turboprop motor.

Selecting the necessary composition of water-methanol mixture and amount of it for injection into the combustion chambers, it is possible practically to increase the fraction of gas-turbine engine by 10%; with this the weight of additional equipment, including capacity for water, required for one minute of work of motor will amount to around 14-18 kg.

British European Airways recommends for aircraft "Viscount" 700-700D with "Rolls Royce-Dart" 506-510 turboprop motors to use water-methanol mixture of the following composition: 62 wt % of distilled water and 38 wt % of methyl alcohol (methanol). Density of water-methanol mixture of the above-mentioned composition (at 15.6°C) should be not lower than 0.9412 and not higher than

0.9445 g/cm^3, and freezing point of such a mixture not higher than -50°C.

Injection into gas-turbine engines instead of water of water-methanol mixture is explained mainly by tendency to remove danger of freezing of liquid in vessel and turbowires on board the aircraft during operation. But sometimes not a water-methanol mixture, but water is injected. Thus, on "Boeing-707" aircraft with TZ-S-3 engines, injection of water is used. Capacity of tank for water is 2645 liters; this quantity suffices for 2.2 min of work of four engines during takeoff.

At temperatures higher than 4.5°C water simultaneously is injected on entrance and into diffuser of motor, and at temperatures lower than 4.5°C it is injected only into diffuser of motor.

5. RADIANT HEAT EXCHANGE AND INTENSITY OF RADIATION OF FLAME

Radiant heat exchange in flame plays a very important role for solution of problems of cooling of walls of combustion chamber during the use of fire evaporators of fuel and during determination of speed of evaporation of drops of fuel atomized by the burner.

In this section the influence of physicochemical properties of fuels on intensity of radiation of flame will be considered. During operation of gas-turbine engines this question is important because during combustion of fuels giving high intensity of radiation of flame, temperature of walls of combustion chamber is sharply increased, which in some cases leads to their warping and burnout.

General rule was established: fuels possessing increased smoke formation and great scale forming ability, as a rule, give higher intensity of radiation of flame. It is assumed that the cause of the high intensity of radiation of some kinds of fuels is the presence in the flame of solid carbon particles.

Research of radiation of flame showed that radiant energy rapidly increases with increase of pressure of gases and to a lesser degree during change of their concentration. During addition to standard fuels of small quantities of substance with great inclination

to smoke formation, for instance benzene, the intensity of radiation of flame is significantly increased.

Thus, what has been said confirms that radiant energy of flame sharply increases in presence in zone of flame of solid products of combustion [14].

Experiments established that during burning in chamber of gas-turbine engine aromatic hydrocarbons give more scale and in their flame a larger amount of solid incandescent particles is observed than during burning of paraffin, naphthenic or olefin hydrocarbons. This also explains that during burning of aromatic hydrocarbons, the greatest intensity of radiation of flame is observed.

Radiation Number of Jet Fuels

In 1960 in the United States in ASTM standard a method of determination of intensity of radiation of flame was introduced; according to this method the intensity of radiation is expressed by radiation number of jet propellants (D-1740-60) [15]. This number is determined by the temperature of flame with constant intensity of its radiation in greenish yellow band of the visible spectrum (2800-7000 Å).

Instrument for determination of radiation number of jet propellants consists of three parts:

1) special wick lamp, which usually is used for determination of smoking point of fuels;

2) apparatus for changing the intensity of radiation of flame, which consists of orange filter, photocell, amplifier and luminometer;

3) thermocouple and potentiometer for direct determination of temperature of flame of lamp.

For determination of radiation number 20 ml of tested fuel and two kinds of standard fuels, isooctane and tetralin are required. Complete physicochemical characteristics of standard fuels used in the given method are listed below (according to M. P. Doss) [59].

Indices	Tetralin	Isooctane
Chemical formula.....	$C_{10}H_{12}$	C_8H_{18}
Density at 20°C, g/cm^3.....	0.9707	0.6919
Melting point, °C.....	-35.8	-107.3
Boiling point, °C.....	206.8	99.2
Coefficient of refraction....	1.5438	1.3914
Viscosity at 20°C, cs.....	2.234	0.502
Heat capacity, kcal/kg.....	0.403	0.489
Heat of evaporation, kcal/kg.	79.3	68.3
Aniline point, °C.....	20	80
Surface tension at 20°C, d/cm	34	18
Flash point, °C.....	77	-9
Smoking point, mm.....	5	40
Ratio C:H.....	10.0	5.3

Radiation number of jet propellants is determined in the following order.

a) Into lamp is poured 20 ml of standard tetralin and at different height of flame four points are taken, which are plotted on curve, showing the dependence of intensity of radiation (in units) on temperature of flame. The last (fourth) point on curve is called nominal and is obtained at such a height of flame, when from tip of flame an insignificant amount of smoke escapes. Temperature of flame, measured at this point, is nominal and enters into calculating formula.

b) Into lamp is poured 20 ml of standard isooctane and also on four points a curve is constructed of dependence of intensity of radiation on temperature of flame.

c) Into lamp is poured sample of tested fuel and also on four points a curve is constructed of dependence of intensity of radiation on temperature of flame.

As a result of conducted measurements there will be obtained (measured) temperatures of flame of tetralin, isooctane and tested fuel with constant intensity of radiation, corresponding to the intensity of radiation of flame of tetralin at the smoking point. Obtained temperatures are substituted in formula, by which radiation number of tested fuel is calculated.

$$\text{Radiation number} = \frac{\text{T of tested fuel} - \text{T of tetralin}}{\text{T of isooctane} - \text{T of tetralin}} \times 100.$$

Radiation Number of Commercial Types of Jet Fuels

Radiation number of commercial types of jet fuels of the United States of the type of aviation kerosenes oscillates from 45 to 58, and of JP-4 fuels with direct distillation reaches 70-80 [16].

Below are described results of research of commercial samples of jet propellants of foreign countries, conducted in 1963.

Country	Fuel	Radiation number	Country	Fuel	Radiation number
England.....	ATK	54	Australia.....	ATK	60
Holland.....	ATK	60	New Zealand...	ATK	57
Denmark.....	ATK	60	Indonesia.....	ATK	58
France.....	ATK	58	India.....	ATK	56
Sweden.....	ATK	48	Burma.....	ATK	49
The United States.....	JP-4	61	Morocco.....	ATK	57

Influence of Intensity of Radiation of Flame on Temperature of Walls of Combustion Chamber of Engine

Works of laboratories of "Pratt Whitney" firm established that the lower the height of sootless flame of fuel, the higher the intensity of radiation of flame. Due to this during work of jet engine on fuels with low smoking point (height of sootless flame) the temperature of walls of combustion chamber of engine will be higher.

Table 15. Influence of Smoking Point of Fuel on Temperature of Walls of Combustion Chamber [16]

Fuel	Smoking point, mm	Temperature of walls of combustion chamber, °C	
		Average	Maximum
Isooctane.....	40	420	540
Aviation Gasoline...	30	430	570
Fuel JP-4.....	25	445	595
Fuel JP-5.....	20	460	620
Benzene.....	10	515	680
Tetralin.....	5	560	730

Influence of Bicyclic Hydrocarbons on Intensity of Radiation of Flame

The greatest intensity of radiation of flame is observed during burning of jet propellants with large content of bicyclic aromatic hydrocarbons. Therefore in specifications of American engine-building firms for jet fuels of the type of ATK aviation kerosenes a content of bicyclic aromatic hydrocarbons not more than 3% is allowed.

In kerosene fractions up to 250°C obtained from native [Soviet] crudes, the content of bicyclic aromatic hydrocarbons is very insignificant and practically rarely exceeds 2%.

In heavier kerosene fractions (250-300°C) the content of bicyclic aromatic hydrocarbons sharply increases (Table 16).

Table 16. Content of Aromatic Hydrocarbons [20]

Temperature of evaporation of kerosene fraction, °C	Content of aromatic hydrocarbons, %		Temperature of evaporation of kerosene fraction, °C	Content of aromatic hydrocarbons, %	
	Monocyclic	Bicyclic		Monocyclic	Bicyclic
Baku crude			Grozny crude		
150-200	11.3	0	150-200	11.6	0
200-250	14.0	2.0	200-250	14.0	2.0
250-300	12.8	13.2	250-300	11.9	7.1

6. HEAT OF COMBUSTION OF JET FUELS

In recent years works were conducted on search for methods of obtaining hydrocarbon (petroleum) fuels possessing high heat of combustion. Such fuels are of special interest for contemporary aviation, since their use promotes lowering of specific consumptions of fuel in engine and, consequently, increase of distance of flights of aircraft or other types of flying apparatuses.

Inasmuch as the most promising and now practically the only raw-material base of production of propellants is crude, hundreds of individual hydrocarbons entering into the composition of crudes and crude products were investigated, and their heat of combustion was determined. It was established that different hydrocarbons evaporating within limits of 100-300°C have different heat of combustion. The lowest heat of combustion (weight) belongs to aromatic hydrocarbons; their highest heat of combustion amounts to 10,250-10,700 kcal/kg. The greatest heat of combustion belongs to paraffin hydrocarbons; their heat of combustion in the same limit of evaporation amounts to 11,250-11,500 kcal/kg. Heat of combustion of naphthenic hydrocarbons close to paraffin also amounts to 11,000-11,250 kcal/kg.

These investigations showed that by means of decrease of content of aromatic hydrocarbons and increase of content of paraffin

hydrocarbons it is possible to somewhat increase the heat of combustion of jet propellants obtained from crude.

In 1959 the American Petroleum Firm "Shell Oil" declared [17] that it had created a commercial type of jet propellant with heat of combustion (lowest) of 10,610 kcal/kg, which is approximately 3.0-3.5% higher than heat of combustion of commercial types of propellants in operation in the United States. According to published data, thanks to almost complete absence in this fuel of aromatic hydrocarbons during operation of motors smoking is removed, scale formation decreases, and the intensity of radiation of flame also sharply decreases, as a result of which temperature of walls of combustion chamber drops and are periods of service of those parts of engine which work in zone of high temperatures extended.

Determination and Calculation of Heat of Combustion of Fuels

Heat of combustion of liquid fuels is expressed in kcal/kg; for chemically uniform substances (for instance, for individual hydrocarbons) the heat of combustion is expressed in kcal/mole.

For gaseous fuels (gases) the heat of combustion is expressed in kcal/m^3.

Highest and lowest heat of combustion of fuels are different. For determination of highest heat of combustion the amount of heat which is liberated during condensation of water vapor, formed owing to combustion of hydrogen contained in the fuel and owing to water contained in the fuel, is considered. For determination of the lowest heat of combustion of fuel the heat of condensation of water is not considered. Therefore the highest heat of combustion of fuel is always greater than the lowest by approximately 500 kcal/kg.

Different heat of combustion of fuels is caused exclusively by their chemical composition and first of all by relationship of carbon and hydrogen.

For thermal calculations the lowest heat of combustion of fuel is always taken. This is caused by the fact that products of combustion of engines going out of the atmosphere have temperature significantly higher than condensation point of water. Consequently, heat of condensation of water vapor in the engine is not used and therefore is not taken into calculations.

In practice two methods of determination of heat of combustion of fuel are used:

a) Method of direct burning of fuel in calorimeter;

b) Method of calculation according to empirical formulas.

Calorimetric Method

Weighed portion of tested fuel is burned in steel thick-walled vessel — bomb, hermetically sealed and filled with oxygen under pressure of 25 atm (tech).

The heat obtained during buring of weighed portion of fuel is transmitted to water of calorimetric bath in which bomb is placed. Heat of combustion of fuels is calculated by increase of temperature of water in calorimetric bath.

During determination of heat of combustion of fuels by calorimetric means, the highest heat of combustion is always obtained.

Method of Calculation According to Empirical Formulas

In daily practice the method of calculation of heat of combustion of fuel with the help of empirical formulas is widely used. This method gives fully satisfactory results.

There exist several empirical formulas for determination of the heat of combustion of fuels by their elementary chemical composition. In the Soviet Union the formulas of D. I. Mendeleyev are used.

Highest heat of combustion

$$Q_в = 81 \cdot C + 300 \cdot H - 26(O - S); \quad [в = h = \text{highest}]$$

lowest heat of combustion

$$Q_н = 81 \cdot C + 246 \cdot H - (O - S) - 6w, \quad [н = l = \text{lowest}]$$

where Q is the heat of combustion of fuel in kcal/kg; C is the content of carbon in fuel in %; H is the content of hydrogen in fuel in %; O is the content of oxygen in fuel in %; S is the content of sulfur in fuel in %; w is the content of water in fuel in %.

Recently several empirical formulas were suggested for calculation of heat of combustion of fuels by their density.

The most satisfactory results were given by formula suggested by Ye. Bass and others for calculation of the highest heat of combustion of fuel, in which density of fuel at 15°C is taken.

Later small changes were introduced in Bass's formula. With the help of formulas of the new type it is possible to calculate the lowest weight and volume heat of combustion by density of fuel at 20°C:

lowest weight heat of combustion

$$Q_{н.в} = (22\,320 - 3780\rho^{20}) \cdot 0{,}54 \text{ kcal/kg}; \quad [н.в = l.w = \text{lowest weight}]$$

lowest volume heat of combustion

$$Q_{н.о} = (22\,320 - 3780\rho^{20}) \cdot 0{,}54\rho^{20} \text{ kcal/liter}. \quad [н.о = l.v = \text{lowest volume}]$$

Operational Value of Volume and Weight Heat of Combustion of Jet Fuels

As already was indicated, the higher the heat of combustion of fuel, the lower its specific consumption.

However, the obtaining from crude of jet propellants possessing high heat of combustion is very hampered.

Petroleum industry produces jet propellant by the method of direct distillation with given characteristics of density, viscosity and fractional composition. Therefore there is practically no possibility of essentially influencing the magnitude of heat of combustion of fuels obtained by the method of direct distillation of crude. This is difficult to acheive also because fuels of the same fractional composition, but obtained from different crudes, are very little different in heat of combustion. Heat of combustion of fuels is given in Table 17.

Table 17. Heat of Combustion of Fuels

Fuel	Density at 20°C, g/cm³	Lowest heat of combustion (average)	
		Weight kcal/kg	Volume kcal/liter
Aviation gasoline.....	0.696	10.500	7.310
The same.....	0.717	10.450	7.410
The same.....	0.737	10.420	7.680
Wide fraction.....	0.755	10.380	7.840
The same.....	0.775	10.360	8.030
Aviation kerosene.....	0.812	10.350	8.400
The same.....	0.826	10.275	8.490
The same.....	0.837	10.250	8.580
Diesel fuel.....	0.865	10.000	8.650
The same.....	0.831	9.850	8.680
Boiler fuel.....	0.990	9.750	9.650

For aircraft accomplishing flights with maximum useful load at distances smaller than the maximum flying range, the requirement of high volume heat of combustion of fuel is unnecessary, since in this case the useful load of aircraft has greater value than propellant weight.

From the table it is clear that the weight heat of combustion of gasoline is approximately 6% higher than the weight heat of combustion of diesel fuel. However the volume heat of combustion of the same diesel fuel is approximately 15% higher than the volume heat of combustion of gasoline. Consequently, during filling of fuel tanks of aircraft with diesel fuel the reserve of thermal energy (calories) will be actually 15% greater than during filling of tanks with gasoline.

Dependence of heat of combustion of jet propellants on their density is shown in Fig. 5.

On aircraft of any type the volume of fuel tanks is a constant magnitude. But due to the unequal density of fuel, weight amount of it which is contained in tanks can be different. For instance, if general volume of fuel tanks of aircraft amounts to 30,000 liters, then during filling of these tanks with fuel T-1 with density of 850 kg/m^3 the propellant weight will amount to 25,500 kg. But if into tanks of this aircraft fuel T-2 with density of 755 kg/m^3 is poured, then propellant weight will amount to 22,650 kg. Thus, with identical volume of tanks the difference in weight of fuel poured in will amount to 2850 kg.

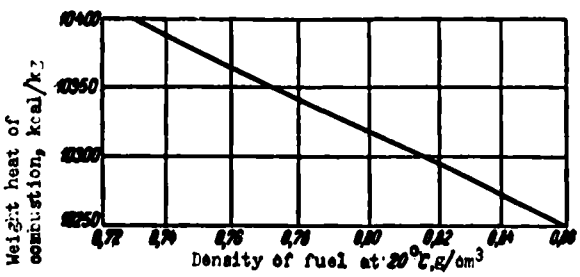


Fig. 5. Heat of combustion of jet propellants depending on their density.

The greater the weight of fuel poured into tanks of aircraft, the greater the flying range of aircraft without additional servicing on the way. From this point of view, if we conditionally take the flying range of aircraft fueled with fuel T-1 as 100%, then during servicing of the same volume of tanks with fuel T-2 the flying range

of aircraft will amount to only 93.2%, i.e., it is lowered 6.8% (Table 18).

Table 18. Influence of Density and Volume Heat of Combustion on Conditional Flying Range

Fuel	Density of fuel at 20°C, kg/m³	Heat of combustion		Relative flying range, %
		Weight, kcal/kg (minimum)	Volume, kcal/liter	
T-1.....	810	10250	8500	100
T-1.....	800	10250	8200	98.8
TS-1.....	775	10250	7940	95.6
T-2.....	755	10300	7770	93.2
B-100/130.	725	10300	7460	90.4

Value of heat of combustion of fuel in operation can be considered also under the following two conditions.

1. Aircraft has limited volume of fuel tanks. In this case to guarantee great distance it is necessary that fuel possesses high volume heat of combustion.

2. Aircraft is limited by weight quantity of fuel, and volume of fuel tanks has large reserve. In this case it is expedient that on servicing fuel was taken possessing high weight heat of combustion.

From this it follows that in the first case to guarantee maximum flying range it is expedient to take fuel of high density, for instance T-1. In the second case to guarantee maximum distance it is expedient to take fuel of low density and high weight heat of combustion, for instance T-2.

In those cases when jet aircraft are operated on internal lines with frequent landings and refueling in intermediate ports, fuel T-2, possessing higher weight heat of combustion, has certain advantages

over fuel T-1 whose weight heat of combustion is almost 100 kcal/kg lower than heat of combustion of fuel T-2.

Density of fuel changes depending on temperature in wide range (Fig. 6). Therefore, even using the same kind of fuel, but fueling aircraft with it at different temperature, poured into tanks different weight amount of fuel can be obtained, and consequently also, different flying range can be ensured.

Let us consider this question in the following example.

During servicing of tanks of aircraft with volume of 30,000 liters with fuel TS-1 at a temperature of 20°C (density 775 kg/m^3) they will contain 23250 kg. During servicing with the same fuel at a temperature of -40°C (density 815 kg/m^3), into tanks of aircraft will be poured 24,450 kg, i.e., 1200 kg more. Consequently, during calculation of flying range of aircraft it is necessary to consider not only the type of fuel, but also its temperature during servicing of aircraft.

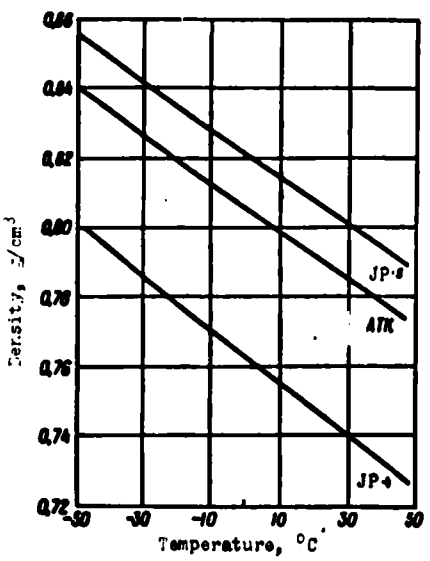


Fig. 6. Change of density of jet propellants of foreign countries depending on temperature.

Thus, high volume heat of combustion for jet propellant is required only when it is necessary to reach maximum flying range with given volume of fuel tanks of aircraft.

During operation of transport aircraft in civil aviation, when maximum pay load of aircraft is desired and when there is possibility and expediency of use of intermediate ports for refueling, the volume heat of combustion of fuels loses its value, since in this case a full fueling of entire volume of fuel tanks of aircraft is not always

economically profitable. To increase to the maximum the transportation of pay loads owing to reduction of propellant weight on board the aircraft is an important problem of civil transport aviation. Due to this in most cases for civil transport aviation, especially working on internal lines, it is important to have fuel with high heat of combustion per unit of weight. Only in those cases when transport aviation is confronted with the problem of reaching maximum distance of non-stop flight is it very important that fuel possess high heat of combustion per unit of volume.

Cubic Expansion of Jet Fuels

During heating of jet propellants their volume is increased. Cubic expansion of oil products obeys general rule of thermal expansion of liquids.

Cubic expansion of fuels is calculated according to the following formula:

$$V_t = V_0(1 + \gamma \cdot {}^\circ t),$$

where V_t is the sought volume in liters or in m^3; V_0 is the volume of fuel at given temperature in liters or in m^3; $^\circ t$ is the temperature of heating of fuel in $^\circ C$; γ is the coefficient of cubic expansion.

For different types of fuels the following magnitudes of coefficients of cubic expansion were found empirically:

Aviation gasolines	0.00118
Fuel T-2	0.00105
Fuel TS-1	0.00099
Fuel T-1	0.00094
Fuel T-5	0.00083

For all types of propellants independently of their fractional composition there is a general rule: the higher the density of fuel,

the less its cubic expansion with identical heating.

If vessel was filled with fuel completely, then during heating due to expansion of fuel part of it will spill outside and be lost; if vessel was hermetically sealed, then during heating it can be destroyed.

During heating of kerosene from 20 to 52°C pressure in filled hermetic vessel was increased from 0 to 250 atm (tech). During heating of jet propellant 10°C its initial volume is increased by 1%.

Borane Fuels

In the United States numerous works are being conducted on the creation of jet and rocket fuels on a base of certain boron hydride compounds: pentaborane (B_5H_9), decaborane ($B_{10}H_{14}$) and others. Special interest manifested in boron hydride compounds is explained by the fact that some of them possess high heat of combustion and in their own physical characteristics are close to contemporary kinds of petroleum jet propellants [18].

Pentaborane (B_5H_9) is a very fluid liquid; its density is around 0.61 g/cm³, boiling point 58°C, freezing point -47°C. At the usual temperatures pentaborance is sufficiently stable and its decomposition is insignificant; at 150°C decomposition is noticeably accelerated, and at 300°C proceeds very fast. Decomposition of pentaborane is accelerated during interaction with water.

Mixtures of vapors of pentaborane with air are explosive and are capable of spontaneous inflammation. Pentaborane is extraordinarily poisonous and causes disease of central nervous system.

Weight heat of combustion of pentaborane is 16,200 kcal/kg, volume 9980 kcal/kg.

In the opinion of foreign authors, an advantage of pentaborane is the high burning rate and stability of flame at high speeds of air flow. This is especially important for ramjet engines.

If we compare the work of turbojet engine having traction of 4500 kg with specific consumption of fuel of 0.80 kg/kg·hr to fuel JP-4 and pentaborane, then it will appear that during work on pentaborane the duration of flight can be increased by 20%, or with equal duration of flight the traction of motor can be increased up to 5320 kg [1].

However further research showed that practical application of boron hydride fuels for gas-turbine engines encounters a number of obstacles which are removed with difficulty. During burning of borane fuels a very high temperature appears and there will be formed a huge quantity of deposits of boric oxide (B_2O_3). Boric oxide is melted at 594°C and up to 1030°C is a viscous mass. In conditions of temperatures of gas-turbine engine boric oxide has the form of molten glass; cooling, it hardens, forming deposits. Therefore no boron hydride compound until now has found practical application as fuel for gas-turbine engines.

Metalorganic Suspensions as Jet Fuel

In recent years abroad, especially in the United States, work has been conducted on the creation of jet propellants with high heat of combustion by means of dispersion in aviation kerosenes of metallic powders with dimensions of particles of 1-20 μ. In the literature the most widely illustrated are materials on the use of powders of beryllium, boron, aluminum and magnesium. However creation of uniform and stable mixtures of kerosene with metallic powders is connected with great difficulties. As a rule, such mixtures are

unstable and after several hours or days are stratified, and powder settles to bottom of vessel.

For creation of more stable suspensions sometimes to kerosene are added various kinds of thickeners in the form of different high-molecular organic compounds (polyisobutylene, wax), and also different soaps (aluminum, sodium and others).

Heat of combustion of 50% of metalorganic suspensions is listed in Table 19.

Table 19. Heat of Combustion of Metalorganic Suspensions [60]

Combustible	Density at 20°C, g/cm³	Highest heat of combustion	
		Weight, kcal/kg	Volume, kcal/liter
Metallic powders			
Beryllium.....	1.32	15000	27300
Boron.....	2.30	13900	32000
Aluminum.....	2.70	7290	19700
Magnesium.....	1.74	6000	10450
Mixture of 50 wt.% of metallic powder +50 wt.% of aviation kerosene			
Beryllium.....	1.13	12620	14250
Boron.....	1.21	12100	14650
Aluminum.....	1.26	8770	11050
Magnesium.....	1.11	8120	9000

From the table it is clear that the weight heat of combustion of metalorganic mixtures of boron and beryllium is approximately 20%, and volume almost 70% higher than aviation kerosene.

According to available source material, metalorganic mixtures have not found practical application because of small stability of

mixtures and due to large deposits of metallic oxides in the engine. It is assumed that such or analogous mixtures can find application in liquid-propellant rocket engines.

Coefficient of Efficiency of Jet Fuels

Coefficient of efficiency as obligatory constant is introduced into English specifications for all types of propellants and aviation gasolines. It is calculated as product of density in degrees API on aniline point of fuel, expressed in °F.

Coefficient of efficiency does not determine absolute value of heat of combustion of fuel, and only guarantees its minimum magnitude. Thus, if coefficient of efficiency of jet propellant ATK is not lower than 4500, this means that heat of combustion of fuel will be not lower than 10,170 kcal/kg (Table 20).

Table 20. Coefficient of Efficiency of Jet Propellants

Fuel	Norms of English specification		Norms of "Shell Oil" Firm
	Coefficient of efficiency	Heat of combustion, kcal/kg	Coefficient of efficiency
JP-1.....	4500	10170	6680
ATK.....	4500	10170	6680
JP-5.....	4500	10170	5380
JP-4.....	5250	10220	7740
Aviation gasoline 115/145...	9000	10500	10370
Aviation gasoline 100-130...	7500	10400	8125
Aviation gasoline 91/96.....	7500	10400	7740

Conversion of density of jet propellants, expressed in degrees API (for calculation of coefficient of efficiency), into density in g/cm^3 is given below:

°API	g/cm^3	°API	g/cm^3	°API	g/cm^3
30	0.876	44	0.806	58	0.747
32	0.865	46	0.797	60	0.739
34	0.855	48	0.786	62	0.731
36	0.845	50	0.780	64	0.724
38	0.835	52	0.771	66	0.717
40	0.825	54	0.763	68	0.709
42	0.825	56	0.755	70	0.702

7. SCALE FORMATION IN GAS TURBINE ENGINES

In the majority of works dedicated to investigation of processes of scale formation in gas-turbine engines, authors arrive at the conclusion that hard scale in engines is mainly petroleum coke, formed as a result of liquid-phase cracking, subsequent pyrolysis and, finally, coking of fuel falling from burner on hot internal wall of chamber.

Soft scale in combustion chamber consists mainly of deposited smoke mixed with residue formed after the decomposition of fuel in liquid phase.

Temperature at which scale appears in combustion chambers of engine can be different from that at which industrial petroleum coke is obtained (750°C). It is more probable that the process of scale formation in chamber of engine proceeds at lower temperatures – approximately at 450-500°C. Difference in temperatures of formation of petroleum coke and scale in combustion chambers of engine is explained by the difference of conditions at which these processes occur. Scale in combustion chamber of engine will be formed in the presence of surplus of oxygen and an open flame, but industrial petroleum coke is obtained only during decomposition of hydrocarbons in the absence of open flame and oxygen.

Hard dense deposits in combustion chamber appear during

simultaneous course of reactions in gaseous and liquid phases. Role and place of each of these types of reactions in processes of scale formation at present still are not determined.

Deposit of scale in gas turbine engines represents a serious problem, since it worsens the characteristics of engines and decreases the duration of period of their service.

Influence of composition of fuel on intensity of radiation of flame has great value. Carbon is the only solid matter which can be formed during the combustion of petroleum fuels. This solid matter under certain conditions of burning can strengthen the intensity of emission of flame.

Smoking During Work of Gas Turbine Engine

Smoking of gas turbine engine indicates certain abnormalities occurring in the processes of combustion of fuel, and first of all the incompleteness of combustion.

Smoke formed during incomplete combustion of fuel consists not of pure carbon, as chemical analysis shows, but of 96.2% carbon, 0.8% hydrogen, and the remaining – oxygen.

In its structure a particle of smoke consists of several layers of atoms with distorted hexagonal lattice reminiscent of the lattice of graphite.

Combustion chambers of contemporary gas turbine engines work on lean mixtures, however, a large part of reactions of burning proceed in zones locally enriched with fuel. Zones are formed as a result of the fact that in the beginning all fuel falls on head part of combustion chamber; holes for feed of secondary air are located all along the length of the chamber. Flame of burning of rich mixture in head part of chamber turns out to be strongly luminescent under the usual operating conditions. Consequently, conditions of burning in

this region must promote the formation of large quantities of smoke.

On process of smoke generation the physicochemical properties of fuel have a significant influence. In case of pure hydrocarbons the inclination to smoke generation for four basic homologic series is changed in the following order: aromatic hydrocarbons – acetylene hydrocarbons – olefins – normal paraffins.

Inclination to smoke generation of aromatic hydrocarbons on the average is 6.2-15.7 times greater than olefin, and 16.2-31.8 times greater than paraffin hydrocarbons. Inclination to smoke generation of olefin hydrocarbons is approximately two times greater than paraffin.

During addition of aromatic hydrocarbons to normal paraffin their smoke generating properties are sharply increased.

In jet propellants of the type of aviation kerosenes and fuels of wide fractional composition there always is contained a certain amount of compounds of sulfur, nitrogen and oxygen. Content of sulfur in jet propellants of the order of 0.10-0.25% is allowed. Content in jet propellants of compounds of nitrogen and oxygen is not standardized, but practically it does not exceed 0.1-0.5%.

Research showed that alkylated compounds of sulfur (mercaptans and disulfides), and also alkylated compounds of nitrogen (amines) possess greater inclination to smoke generation than the corresponding hydrocarbons. Aryl mercaptans and sulfides have almost identical, and aryl amines – significantly smaller inclination to smoke generation as compared with corresponding hydrocarbons. Increase of content of oxygen in fuels leads to decrease of inclination of fuel to smoke generation. Methyl alcohol burns without formation of smoke. Compounds with high content of oxygen, for instance, methyl acetate, form smoke only with very great height of flame.

Concentration of sulfur, nitrogen and oxygen in standard grades of jet propellants is so insignificant that the presence of these impurities is not an influence yielding to measurement on the inclination of fuel to formation of smoke.

Contemporary gas turbine engines eject little smoke; this is explained by the fact that smoke formed in head part of chamber almost completely burns during passage through it.

Methods of Appraisal of Scale-Forming Properties of Jet Fuels

During development of new grades of jet propellants their scale-forming properties are determined and are checked by means of test on full-scale gas turbine engines.

Scale-forming properties of commercial grades of jet propellants, entering into operation are regularly checked with the help of laboratory methods (Table 21).

Table 21. Methods of Determination of Smoking Point

Indices	Soviet Union	England	United States
Specification (standard)	GOST 4338-48	JP-57/55	ASTMD-132-58
Amount of fuel, ml	10	20	20
Permissible divergences between parallel determinations, mm.	1	2	2

In specifications of foreign countries two methods are listed of laboratory appraisal of scale-forming properties of jet propellants.

1. Smoking point is used for checking the scale-forming properties of jet propellants of type of aviation kerosenes.

2. Coefficient of smoking and volatility (KDL) is used for checking the scale-forming properties of jet propellants of wide

fractional composition.

Smoking point is the maximum height of sootless flame, expressed in millimeters: it is determined with the help of special wick lamp (Fig. 7).

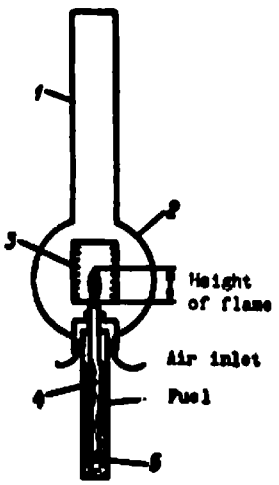


Fig. 7. Diagram of instrument for determination of height of sootless flame (smoking point). 1 – lamp glass, 2 – combustion chamber, 3 – scale of measurement of height of flame, 4 – wick, 5 – cylinder for fuel.

Experiments established that the greater the height of the smoking flame, the less smoke and carbon deposits (scale) will be formed during combustion of fuel in gas turbine engine.

According to American method of ASTM [18], during determination of smoking point of jet propellants the correctness of indication of instrument is checked by scale of standard mixtures (Table 22).

Table 22. Standard Mixtures for Checking Instruments During Determination of Smoking Point of Fuels

Content % by volume		Smoking point at 760 mm Hg, mm
Toluene	Isooctane	
40	60	14,7
25	75	20,2
15	85	25,8
10	90	30,2
5	95	35,0

If during determination of smoking point of fuels the atmospheric pressure is more or less than 760 mm Hg, it is recommended to introduce the corresponding correction.

Smoking point, mm.....	35	30	25	20	15
Correction for each 10 mm Hg above or below 760 mm Hg, mm.	0.38	0.29	0.23	0.19	0.17

Works of recent years established that there exists a direct dependence between the smoking point of fuel and the intensity of radiation of flame (see Table 15).

On the basis of conducted research at present the smoking point as index of scale-forming properties of jet propellants is introduced into many specifications of foreign countries (Table 23).

Table 23. Scale-Forming Characteristics of Jet Propellants

Country	Fuel	Specification	Smoking point not below mm	Coefficient of smoking and volatility, not below
Soviet Union	T-1	GOST 10227-62	20	—
	TS-1		25	—
	T-2		25	—
England	Avtour-40	DERD-2482	—*	—
	JP-4	DERD-2486	—	54
	Avtour-50	DERD-2494	—	—
	JP-5	DERD-2498	18	—
Canada	Avtour 50	3-dr-23c	—	—
	JP-4	3-dr-22c	—	52
France	Avtour-40	Air-3405	—	—
	JP-4	Air-3407	—	54
	JP-5	Air-3404	18	—
The United States (military fuels)	JP-3	MIL-J-5624E	—	52
	JP-4	MIL-J-5624E	—	52
	JP-5	MIL-J-5624E	19	—
	JP-6	MIL-F-25656	20	—
The United States (civil fuels)	Type-A (Avtour-40)	ASTMD-2	20	—
	Type-B (JP-4)	ASTMD-2	—	54
	Type A-1 (Avtour-50)	ASTMD-2	20	—

*Line means that the given index is not standardized.

Coefficient of smoking and volatility is used for appraisal of scale-forming properties of jet propellants of wide fractional composition. It is determined by the sum of two values: smoking point in

millimeters plus the product of index 0,42 multiplied by amount of fraction evaporating up to 204,4°C, expressed in percent by volume.

Tests on engine established that the higher the coefficient of smoking and volatility of fuel, the less carbon depostis (scale) will be formed in the engine during combustion of given fuel.

In specifications for jet propellants of wide fractional composition of foreign countries the coefficient of smoking and volatility is allowed not below 52-54 (see Table 23).

Dependence of Scale Formation on Physical and Chemical Characteristics of Jet Fuels

In recent years the acuteness of problem of scale formation, especially in civil transport aviation, not only did not lessen, but even was somewhat increased. This is caused by the sharp increase periods of work of gas turbine engines between repairs and, consequently, by increase of time of accumulation of scale in the engine.

Formerly periods of work of gas turbine engines did not exceed 500 hr; at present they reach 1500 hr and more.

In 1960 in the United States [49] tests were conducted of numerous grades of fuels on full-scale turbojet engine Boeing 502-10C basically to show the regularities of influence of physicochemical indices of fuels on scale formation in gas turbine engines.

Influence of density of fuels. With increase of density of fuels, scale formation in gas turbine engine is increased. With increase of density of fuels from 0.740 to 0.850 g/cm^3 scale formation increases slowly, with density of fuels higher than 0.850 g/cm^3 – very sharply (Fig. 8).

Influence of actual resins. For tests fuels were taken with content of actual resins from 1 to 20 mg per 100 ml. With this an almost direct dependence was established: with increase of content

of actual resins in fuel, scale formation in gas turbine engine increases (Fig. 9).

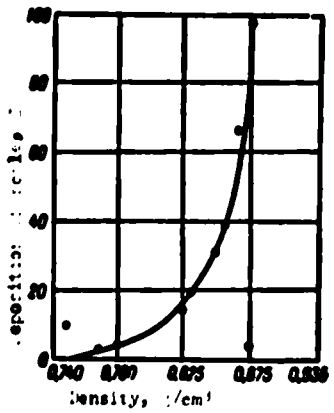


Fig. 8. Influence of density of fuel on formation of scale in combustion chamber of turbojet engine.

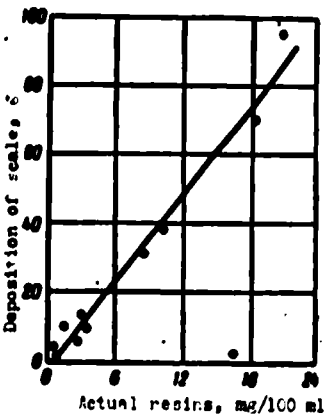


Fig. 9. Influence of content of actual resins on formation of scale in combustion chamber of turbojet engine.

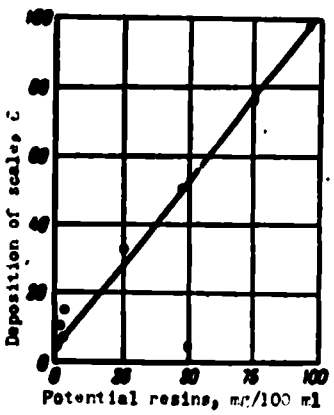


Fig. 10. Influence of content of potential resins on formation of scale in combustion chamber of turbojet engine.

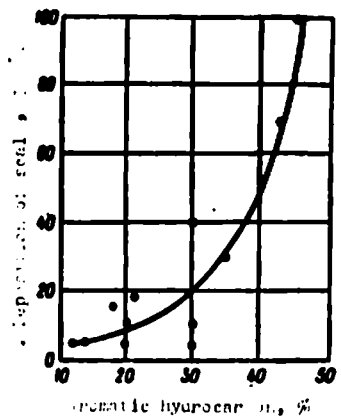


Fig. 11. Influence of content of aromatic hydrocarbons in fuels on formation of scale in combustion chamber of turbojet engines.

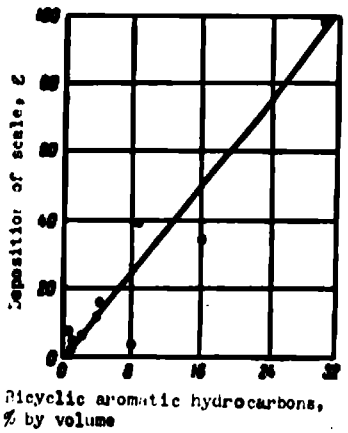


Fig. 12. Influence of content in fuels of bicyclic aromatic hydrocarbons on formation of scale in combustion chamber of turbojet engine.

Influence of potential resins. Content of potential resins in fuels, taken in test, oscillated from 2 to 98 mg per 100 ml. With this a direct dependence was established: with increase of content of resins in fuel the deposition of scale in gas turbine engine increases proportionally (Fig. 10).

Influence of aromatic hydrocarbons. Content of aromatic hydrocarbons in fuels, taken in test, oscillated from 12 to 45%. With this

the rule was established: with increase of content of aromatic hydrocarbons from 12 to 30% an essential increase of scale-formation in engine in most cases is not observed. With content of aromatic hydrocarbons more than 30% scale-formation in engine spreads sharply (Fig. 11).

Influence of bicyclic aromatic hydrocarbons. In majority of investigated fuels the content of bicyclic aromatic hydrocarbons amounted to 1-4%. With content of them in fuels more than 4% scale formation in the engine sharply increases (Fig. 12).

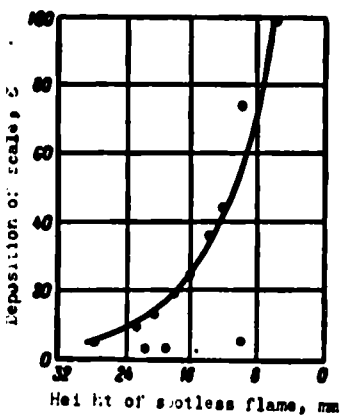


Fig. 13. Influence of height of sootless flame of fuels on formation of scale in combustion chamber of turbojet engine.

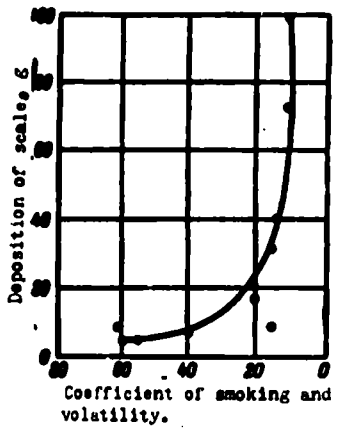


Fig. 14. Influence of coefficient of smoking and volatility of fuels on formation of scale in combustion chamber of turbojet engine.

Influence of height of sootless flame. Height of sootless flame of investigated fuels was within limits of 10-28 mm, i.e., research included wide range of fuels. Tests showed that there exists a direct connection between the height of sootless flame and scale-forming properties of fuels. With decrease of height of sootless flame of fuel scale formation in gas turbine engine is increased (Fig. 13).

Influence of coefficient of smoking and volatility. Tests of fuels in engine showed that coefficient of smoking and volatility does not always express the real scale-forming properties of fuels.

With decrease of coefficient of smoking and volatility of fuels

from 60 to 20 scale formation in motor is increased insignificantly. With further lowering of coefficient of smoking and volatility of fuels (from 20 to 10), scale formation in engine increase approximately 5 times (Fig. 14).

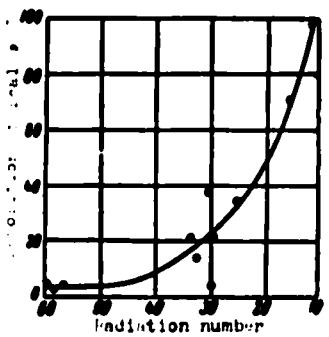


Fig. 15. Influence of radiation number of fuels on formation of scale in combustion chamber of jet engine.

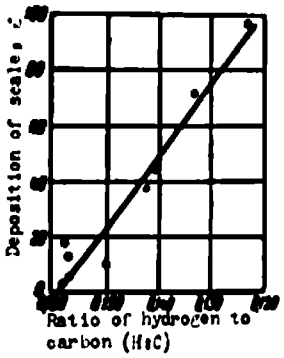


Fig. 16. Influence of ratio of hydrogen to carbon of fuels on formation of scale in combustion chamber of turbojet engine.

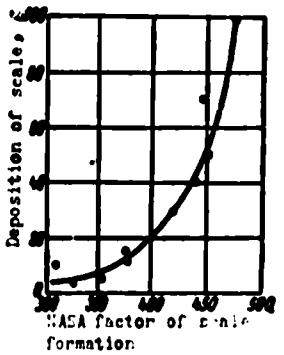


Fig. 17. Influence of NASA factor of scale formation of fuel on formation of scale in combustion chamber of turbojet engine.

Relation between radiation number and scale-forming properties of fuels. As is known, the radiation number of jet propellants is the index of intensity of radiation of flame jet and to a significant degree is determined by the content in fuels of aromatic hydrocarbons.

In given investigations fuels with radiation number from 10 to 60 were tested in engine.

With lowering of radiation number of fuel scale formation in gas turbine engine is increased (Fig. 15).

Influence of ratio of hydrogen to carbon. Magnitude of ratio of hydrogen to carbon is determined by the chemical composition of fuel and in particular by the content in the fuel of aromatic hydrocarbons. The more aromatic hydrocarbons in the fuel and the less paraffin, the lower the magnitude of ratio of hydrogen to carbon (H:C).

Precisely for this reason researchers very frequently use magnitude of ratio of hydrogen to carbon for determination of scale-forming characteristics of jet propellants.

During test of fuels in engine a direct dependence was established – with decrease of magnitude of ratio of hydrogen to carbon scale formation in gas turbine engine is increased (Fig. 16).

Influence of NASA factor. In the United States for appraisal of scale-forming properties of jet propellants the NASA factor is widely used, which is calculated with the help of the following empirical formula:

$$\text{NASA factor "K"} = (t^{\circ}_{50\%} + 600) \cdot 0{,}7 \frac{(H:C) - 0{,}207}{(H:C) - 0{,}250},$$

where $t^{\circ}_{50\%}$ is the temperature of boiling away of 50% of fuel in °F.

NASA factor "K" is a dimensionless magnitude; practically it oscillates from 300 to 500.

Tests of different grades of fuels in engine showed that there exists a clearly expressed dependence: with increase of NASA factor "K" scale formation in gas turbine engine is increased (Fig. 17).

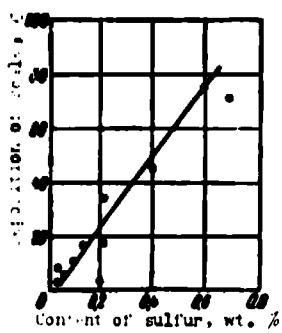


Fig. 18. Influence of content of sulfur in fuel on formation of scale in combustion chamber of turbojet engine.

Influence of sulfur. In jet propellants of foreign countries the permissible total content of sulfur amounts to 0.4%, in native [Soviet] fuels – not more than 0.25%.

Fuels with content of sulfur of 0.05-0.70% were tested in engine. Tests showed that with increase of content of sulfur in the fuel scale formation in gas turbine engine is increased (Fig. 18).

Influence of diesel index. Diesel index

is widely used in all countries of world for indirect appraisal of inflammable properties of diesel fuels; it is calculated according to the following empirical formula:

$$\text{Diesel index} = (1{,}8A + 32)\frac{1{,}145}{\rho} - 1{,}315),$$

where A is the aniline point of fuel in $^{\circ}C$, ρ is the density of fuel at $15.5^{\circ}C$.

Analysis of constants entering into the formula shows that the more aromatic hydrocarbons in fuel and consequently, the higher the density of fuel, the lower the diesel index and the worse the inflammability of fuel.

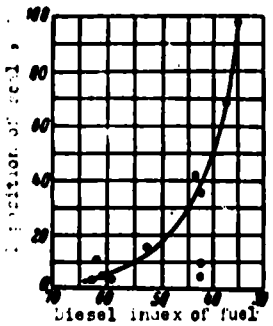


Fig. 19. Influence of diesel index of fuel on formation of scale in combustion chamber of turbojet engine.

An attempt was made to clarify the dependence of scale formation on magnitude of diesel index of tested fuels: this is of interest inasmuch as the diesel index is determined basically by density of fuel and by content in it of aromatic hydrocarbons.

Test showed that the lower the diesel index of fuel, the higher the scale formation in gas turbine engine (Fig. 19).

Smoking of Gas Turbine Engines

For development and creation of relatively cheap grade of jet propellant for low capacity gas turbine engines of ground transport (automobile) the influence of different physicochemical indices of fuel on smoking of engines was specially investigated [49]. Research showed that all those physicochemical properties of fuels which cause increase of scale formation in engine promote intensification of smoking of gas turbine engine.

Influence of Chemical Composition of Fuels on Scale Formation

Decisive influence on scale formation in gas turbine engines is chemical composition of fuels.

Main groups of hydrocarbons entering into the composition of Jet propellants are arranged in the following sequence with respect to intensity of scale formation: paraffin < < naphthenic < unsaturated < monocyclic < < aromatic < bicyclic aromatic [19] (Table 24).

Table 24. Scale-Forming Ability of Hydrocarbons

Composition of mixture	Formation of carbon deposits during burning of different groups of hydrocarbons g/liters		
	Paraffin-naphthenic	Monocyclic	Bicyclic
1.0	21	140	220
1.5	18	115	180
2.0	10	85	160
2.5	8	70	150

Results of research in small-size chamber [5] also showed that the greatest scale-forming ability belongs to aromatic hydrocarbons, and the least – to paraffin naphthenic.

Formation of Scale on Burners of Gas Turbine Engines

Formation of scale on burners of gas turbine engines presents a great danger and in some cases can lead to serious damage of engine.

Scale on burners is deposited gradually in the form of dense carbon mass and will form crown with expandes edges. In the beginning carbon crown narrows somewhat the angle of atomizing of fuel, and then with its increase the angle of atomizing is narrowed so much that from the burner emerges not a torch of atomized fuel, but a stream.

Disturbance of atomizing of fuel causes disturbance of process of carburetion and combustion. With this, as a rule, flame jet shifts and is extended, which in some cases leads to burnout of walls of combustion chamber and even of blades of gas turbine.

It is assumed that scale formation on burners is caused by two factors:

Table 25. Composition of Scale from Burners of Gas Turbine Engines

[illegible] of fuel on which the turbine worked	Composition of scale on burners, wt.%	
	organic part	inorganic part
[illegible]	99.1	[illegible]
[illegible]-1	98.1	0.9
[illegible]-2	98.9	1.1

1) structural incompleteness of combustion chamber and, in particular, insufficient air cleaning of burners;

2) great scale-forming ability and, in particular, increased content of high-boiling aromatic, actual resins and sulfur compounds in fuel.

Typical composition of scale formed on burners of gas turbine engines is listed in Table 25.

8. THERMAL STABILITY OF JET FUELS

Jet propellants (hydrocarbon) under the influence of high temperatures and oxygen (air) are oxidized. As a result of oxidation in the fuels the content of actual resins is increased, acidity is increased and insoluble deposits are formed.

Table 26. Oxidation of Jet Propellants Under the Influence of High Temperatures [61]

Temperature, °C	Fuel T-1			Fuel TS-1	
	Acidity mg KOH/100 ml	Actual resins mg/100 ml	Insoluble deposit, mg/100 ml	Acidity mg KOH/100 ml	Actual resins mg/100 ml
80	0,35	4,0	0	0,25	10,5
90	0,35	4,0	0	0,25	11,0
100	0,40	6,0	0	0,35	10,5
110	1,27	16,5	0	0,90	12,5
115	2,6	17,0	4	1,53	12,0
120	3,82	20,5	5	1,53	15,5
125	4,72	28,0	7	2,52	15,0
130	6,17	34,5	8	3,16	19,0
135	6,73	—	10	—	22,5

Intensity of oxidation of fuel under the influence of high temperatures expressed by the term "thermal stability." The higher the thermal stability of fuel, the slower fuel is oxidized and the less insoluble deposits will be formed in it.

The most important external factors which are strong influence on oxidation of fuel and formation in it of resins and insoluble deposits are: temperature, oxygen (air) and catalytic action of different metals.

All other conditions being equal, with increase of temperature, oxidation of jet propellants is increased (Table 26).

Methods of Determination of Thermal Stability of Jet Fuels

In the Soviet Union and abroad methods of estimating the thermal stability of jet propellants are widely used in which with some approximation conditions of work of fuel system of aircraft (supersonic) are reproduced. At constant given temperature the fuel is pumped through a preheater and filter (thickness of 10-20 μ) and speed of buildup of pressure drop on filter is measured, which corresponds to speed of plugging of pores of filter by insoluble deposits formed in the fuel, or time is measured in which pressure drop on filter reaches given value.

As illustration in Table 27 are given data on determination of thermal stability of jet propellants ASTM D-1660-59T by American standard method.

Table 27. Conditions of Determination of Thermal Stability of Jet Propellants

Indices	ATK and JP-5	JP-4
Temperature of heating of fuel in preheater, °C	204.4	148.9
Temperature of the filter, °C	260.0	204.4
Rate of pumping of fuel, kg/hr	2.72	2.72
Duration of pumping of fuel, min	300	300

During determination of thermal stability of jet propellants by this method the quality of fuel is estimated by two indices:

1) clogging of filter of apparatus after 300 min of pumping of fuel, expressed by measurement of pressure drop (on filter), does not have to exceed norms shown in specifications for fuels (Table 28);

2) deposits in preheater of apparatus after termination of test (after 300 min) must be less than 3; this signifies the following: if diameter of spot formed by deposit in tube of preheater is larger

than 1/4" (6.3 mm) and color of this spot is equal to 3 units or more according to ASTM standard color scale, then fuel did not withstand tests.

Table 28. Thermal Stability of Jet Propellants of Foreign Countries

Country	Fuel	Specification	Change of pressure drop on filter after 5 hr test, mm Hg	Deposits in preheater in units of ASTM color scale
England	JP-4	DERD-2486	Not more than 330	Not more than 3
	JP-5	DERD-2488	" 330	" 3
The United States (military fuels)	JP-4	MIL-J-5624E	" 330	" 3
	JP-5	MIL-J-5624E	" 330	" 3
	JP-6	MIL-F-25656	" 254	Light-brown
The United States (civil fuels)	Type-A (Avtour-40)	ASTM-D-2	" 300	Not more than 3
	Type-B JP-4	ASTM-D-2	" 300	" 3
	Type-A-1 (Avtour-50)	ASTM-D-4	" 300	" 3

Influence of Actual Resins on Formation of Insoluble Deposits in Jet Fuels

Formation of insoluble deposits in jet propellants is not only the result of deeper oxidation of resins contained in fuels. With the same content of actual resins (depending on the chemical composition of fuel and presence in it of certain compounds of sulfur, nitrogen and others) a different amount of insoluble deposits can be formed. Thus, with content in initial fuel of 2 mg/100 ml of actual resins at 150°C in fuel TS-1 there will be formed 6 mg/100 ml, and in fuel

Table 29. Influence of Resins on Formation of Insoluble Deposits in Jet Propellants TS-1 and T-1

Fuel	Content of resins in fuel, mg/100 ml			Thermal stability according to method of GOST 9144-59, mg/100 ml
	Actual	Adsorption	Potential	
T-1	2	13	19	21
	4	15	20	20
	6	22	19	25
TS-1	0	6	13	6
	1	6	13	5
	2	6	16	6
	3	6	10	7

T-1 20 mg/100 ml of insoluble deposits will be formed (Table 29). Consequently, content of actual resins in fuels is not index of thermal stability of jet propellants.

Influence of Metals on Thermal Stability of Fuels

From the literature it is known that the presence in fuel of certain metals, especially copper and its alloys, significantly accelerates oxidation of fuels during their storage. Oxidation is accompanied by buildup of tarry substances and increase of acidity of fuels.

Recent works showed that at high temperatures the catalytic influence of metals on the processes of oxidation of jet propellants is increased; with this in fuel not only the content of actual resins increases, but also the amount of insoluble deposits.

Different metals exert unequal catalytic action on oxidation of jet propellants. Thus, with the same conditions copper and its alloys exert stronger catalytic action than steel and aluminum (Table 30).

Table 30. Influence of Metals on Thermal Stability of Jet Propellants T-1 and TS-1 (Test was Conducted for 10 hr at 120°C)

Fuel and metal introduced into it	Insoluble deposit mg/100 ml		Actual resins, mg/100 ml		Acidity, mg KOH/100 ml	
	Without blowing through of air	With blowing through of air 50 ml/min	Without blowing through of air	With blowing through of air 50 ml/min	Without blowing through of air	With blowing through of air 50 ml/min
T-1						
Bronze VB-24.....	5,0	56	13	141	3,6	27,5
Steel 12 + N3A.....	2,7	3,2	12	23	1,4	3,9
Aluminum AL-9.....	2,3	4,0	10	16	1,9	3,0
TS-1						
Bronze VB-24.....	2	2	3	9	0,6	0,6
Steel 12KhN3A.....	0	0	2	4	0,6	1,1

Role of Oxygen in Formation of Insoluble Deposits in Jet Fuels

Influence of atmospheric oxygen on intensity of oxidation of jet propellants and on formation in them of insoluble deposits is shown especially convincingly in works of Shimonayev and others [20]. In these works oxidation of jet propellant T-1 was conducted in medium of air and in medium of nitrogen.

During oxidation in medium of air at 200°C for 50 min the content of deposits in fuel T-1 reached 39 mg/100 ml. During oxidation of the same sample of fuel in medium of nitrogen no deposit in fuel was observed (Table 31).

Table 31. Thermal Stability of Jet Propellant at Different Temperatures

Duration of oxidation, min	Quantity of deposits in mg/100 ml during oxidation					
	in medium of air at				in medium of nitrogen at	
	120°C	150°C	200°C	250°C	200°C	250°C
10	Absent	3	23	11	Absent	
20	"	4	33	12	"	
30	"	5	36	15	"	
50	1	7	39	16	"	

Influence of Prolonged Storage of Jet Fuel on Its Thermal Stability

Research established that during prolonged storage the thermal stability of jet propellants drops without noticeable change of the other physicochemical propellant properties. This phenomenon is explained, obviously, by the fact that during prolonged storage such oxidizing processes occur which are incompletely detected by the existing methods of analysis, but lead to significant lowering of thermal stability of fuels (Table 32).

Table 32. Lowering of Thermal Stability of Jet Fuel During Prolonged Storage

Indices	Up to storage	After storage for 1 year
Temperature of beginning of formation of deposits in fuels, °C.....	140	140
Average speed of buildup of pressure on filter due to its clogging by deposits, mm Hg/min*.....	0.2	1.8

*Test was conducted at 160°C.

Thermal Stability of Commercial Grades of Fuels

The most important operational indices of thermal stability of jet propellants are minimum temperature of heating of fuel, at which insoluble deposits begin to be formed in fuel, temperature of maximum deposit formation in fuels and, finally, speed of formation of deposits, which practically can be determined by speed of buildup of pressure drop on filter due to its clogging with insoluble deposits (Table 33).

Table 33. Characteristics of Thermal Stability of Jet Propellants [21]

Fuel	Temperature of beginning of formation of deposits in fuel, °C	Temperature of the greatest deposit formation, °C	Time during which filter clogs, min	Speed of buildup of pressure on filter mm Hg/min
T-1	110	140	120—180	1,9—2,8
TS-1	140	160	120—300	1,1—2,8
T-5	140	170	50—120	2,8—6,9

As can be seen from data of the table, without formation of deposits fuel T-1 can work at temperatures to 110°C, and fuel TS-1 — to 140°C.

9. FORMATION OF TARRY SUBSTANCES IN JET FUELS

Contemporary grades of jet propellants constitute a fraction obtained from crude by method of direct distillation and subsequent purification of this fraction.

During prolonged storage under the influence of temperature, atmospheric oxygen, light and catalytic action of metals some groups of hydrocarbons are able to be oxidized with formation of tarry substances.

The highest oxidizing stability belongs to paraffin and naphthenic hydrocarbons. Some aromatic hydrocarbons, for instance, hydrocarbons having double bond in lateral chain, are insufficiently stable. During prolonged storage these compounds are oxidized with formation of tarry substances. The lowest stability belongs to unsaturated hydrocarbons: therefore their content in jet propellants is strictly limited. In native [Soviet] grades of jet propellants a content of unsaturated hydrocarbons is permitted not more than 2.4% (iodine number 3.5), and in jet propellants of foreign countries – not more than 5% (bromine number not more than 5); practically it does not exceed 1%.

In the initial period of oxidation of unsaturated hydrocarbons the formed products of oxidation are completely dissolved in fuel and in some cases color in a yellow color of different intensity. With

further and deeper oxidation the content of tarry substances in fuels is increased and solubility in them decreases. With strong resinification of fuel part of tarry substances begins to precipitate from solution in the form of sticky tarry mass, settling on bottom of the container or on walls of pipelines.

Actual Resins in Jet Fuels

Actual resins is the name for complicated products of oxidation, polymerization and condensation of hydrocarbons contained in jet propellants and formed during their evaporation in stream of air or steam.

Table 34. Content of Resins in Jet Propellants

Country	Fuel	Specification	Content of resins, mg/100 ml	
			Potential	Actual
Soviet Union	T-1	GOST 10227-62	—	6
	TS-1		—	5
	T-2		—	5
England	Avtour-40	DERD-2482	6	3
	JP-4	DERD-2486	14	7
	Avtour 50	DERD-2494	6	3
	JP-5	DERD-2498	14	7
France	Avtour-40	Air-3405	—	6
	JP-4	Air-3407	14	7
	JP-5	Air-3404	14	7
Canada	Avtour-50	3-GP-23c	14	7
	JP-4	3-GP-22c	14	7
The United States (military fuels)	JP-3	MIL-J-5624E	14	7
	JP-4	MIL-J-5624E	14	7
	JP-5	MIL-J-5624E	14	7
	JP-6	MIL-F-25558	10	—
The United States (civil fuels)	Type-A (Avtour-40)	ASTM D-2	14	7
	Type-B (JP-4)	ASTM D-2	14	7
	Type-A-1 (Avtour-50)	ASTM D-2	14	7

Content of actual resins in jet propellants is strictly limited by specifications (Table 34).

High content of actual resins in jet propellants represents a danger and may cause the following complications during operation of gas turbine engines.

1. With high content of actual resins in jet propellants increased formation of carbon deposits in burners and in some cases in combustion chambers of motors is observed.

2. During work on strongly resinified fuels tarry substances precipitate from fuel in pipelines, in fuel flow control assembly and

on filters of fine purification of aircraft.

Deposits of tarry substances can disturb work of fuel flow control assembly, but in the presence of water cause plugging of mesh (pores) of netted and paper filters of fine purification.

According to the method accepted in Soviet Union and abroad, actual resins in jet propellants are determined by evaporation of 25 ml of fuel in glass beaker during heating of it in oil or electrical bath and simultaneous blowing through of stream of heated air (USSR) or superheated (232°C) steam (the United States and others).

Amount of actual resins is determined by weighing the residuum of unevaporated tested fuel after full evaporation, and is expressed in milligrams in scaling to 100 ml of fuel.

Table 35. Definition of Actual Resins in Jet Propellants

Indices	USSR, GOST 1567-56	England, JP-131/58T	The United States ASTM-D-381-58T
Temperature of bath, °C	180 ± 3	232-246	232-246
Blowing through during evaporation	Stream of air	Stream of steam	
Temperature of steam, °C	-	232	232
Permissible divergences between parallel determinations, mg	Up to 15 not more than 2	Up to 5 not more than 1; From 5 to 10 Not more than 2	Up to 5 not more than 1; From 5 to 10 Not more than 2

Standard conditions of determination of actual resins in jet propellants are listed in Table 35.

Experiments showed that during determination of actual resins in jet propellants of type of aviation kerosenes during evaporation in stream of air and in stream of superheated steam (232°C) approximately identical results are obtained (Table 36).

Table 36. Content of Actual Resins (in mg/100 ml)

Samples of fuel TS-1	Method GOST 1567-56 (evaporation in stream of air)	Method P-131/58T (evaporation in stream of vapor)
1	2.8	3.1
2	2.9	2.7
3	3.8	4.1
4	8.7	5.9
5	6.4	6.1
6	10.4	11.0

Factors Influencing the Resinification of Fuels

The greatest influences on oxidation and resinification of fuels during their storage in fuel storage tanks are exerted by: temperature, surface of contact of fuel with air, metals and water.

High temperature accelerates the processes of oxidation and resin formation. Therefore in summer period, especially in southern regions, during storage of fuel in ground containers tarry substances in fuels are formed faster than during their storage in winter or in the summer in underground containers. Thus, in one experiment during storage of fuel for 5 months at 15-20°C in it was formed 9 mg of resins per 100 ml, and during storage of the same fuel in another region at 35-38°C 53 mg of resins per 100 ml, i.e., at high temperature resinification of fuel proceeded 6 times faster.

Water occurring in fuel, for instance during storage of fuels on water cushion significantly accelerates oxidation and resinification of fuels. Therefore for protection of fuel from resinification it is necessary to remove water from fuel.

Surface of contact of fuel with air, determined by degree of filling of container with fuel during storage, exerts great influence on processes of oxidation and resinification of fuels. The larger the surface of contact of fuel from air or the greater the volume of air space of cistern not filled with fuel, the faster the fuel is oxidized and resinified. To lower the rate of oxidation and resinification of fuels it is necessary more fully to fill cistern with fuel and to close hatches of cistern more tightly.

It was established that the strongest catalysts are copper and lead. In the presence of these metals oxidation and resin formation occur especially fast. This precisely explains the fact that autogasolines are resinified especially fast in tanks of automobiles

Table 37. Action of Metals on Resinification of Fuels (up to Storage of Fuel 5 mg of Resins is Contained)

Fuel	Content of actual resins, mg/100 ml	
	Storage 30 days	Storage 60 days
Without metal	7	8
With iron	25	33
With zinc	31	46
With aluminum	28	40
With lead	48	162

where copper grids are fixed or there is soldering of tanks with copper (Table 37).

Catalytic action of metals, accelerating resinification of fuel, can be weakened by introduction into fuel of excess amount of antioxidants or deactivators of metals.

Protection of Fuels From Oxidation and Resinification

In order to delay or completely to remove resinification of jet propellants in the process of their prolonged storage, special additives – antioxidants are added to fuels.

In practice of foreign countries two types of additives are added to jet propellants:

1) antioxidants;

2) deactivators of metals.

As antioxidants in various countries different types of compounds are used (Table 38).

Mechanism of action of antioxidants added to fuel consists of their reaction with strongly activated molecules – initiators of onset of chain reactions which leads to break of reaction chains of autoxidation.

During storage, antioxidant added to fuel gradually is expended, and therefore action of antioxidant is limited by certain period of time, after which its effectiveness in the beginning drops, and then is ceased. And if fuel is saved further, its accelerated resinification can begin.

Table 38. Antioxidants used in Industry for Stabilization of Jet Propellants and Aviation Gasolines [21]

Antioxidant	Composition of antioxidant	Addition of antioxidant to fuel, %
USSR		
Wood-tar, grade "B" (GOST 3141-46)	Mixture of polyphenols	0,005—0,10
FCh-16 (VTU 590-56)	Mixture of phenols	0,05—0,10
Paraoxydiphenylamine (TU 36H9-52)	Paraoxydiphenylamine	0,005
England and USA		
Topanol "A"	2,4-Dimethyl-6-tert-butylphenol	0,03—0,08
Topanol "O"	2,6-Di-tert-butyl-4-methylphenol	0,03—0,08
JUOP No. 5	NN-Di-sec-butyl-p- phenylene diamine	0,002—0,004
du Pont No. 22	n-Butyl-p-aminophenol	0,002—0,005
Topanol "M"		
JUOP No. 4		
du Pont No. 5		
Tenamene No. 1		

*The JUOP entries may well be fuels JP-4 and JP-5 noted previously. [Tr. Ed. Note]

Deactivators of metals added to fuel remove or sharply lower the activity of metallic catalysts, transforming them into metalorganic complex compounds or into such complex compounds in which atom of metal because of space difficulties will possess lowered catalytic activity. With this it is necessary to consider that deactivators of metals do not affect the speed of noncatalytic oxidation of fuels.

One of the best deactivators of metals, which in foreign countries is added to jet propellants in amount of 5.5 g/1000 liters is considered N-N-disalicylidene-1, 2-diaminopropane.

During oxidation of fuel in the presence of metals heterogeneous catalysis is observed, and metal exerting the catalytic action is in ionic state. In this case the action of deactivator of metals reduces to the fact that they form with ions of metals complex compounds of nonionic character. In such complex compounds metal does not manifest its catalytic effect and consequently does not accelerate the process of oxidation of fuel (Table 39).

establish that the indicated phenomena appear during prolonged storage of jet propellants in contact with sea water. Formation in fuel of tarry deposits and hydrogen sulfide is the result of vital activity of a special type of bacteria, which influencing sulfates contained in sea water, liberate hydrogen sulfide [16] and form tarry products.

In some cases contamination of fuels with tarry deposits and hydrogen sulfide proceeds so intensely that fuel after storage becomes not fit for use.

To remove this danger it is suggested to add to sea water which is in contact with fuel, 1.5-2.0% sodium or potassium tetraborate [22].

10. CORROSION AGGRESSIVENESS OF JET FUELS

Existing grades of petroleum jet fuels consist of hydrocarbons, which do not cause corrosion of metals. Corrosion aggressiveness of some grades of jet propellants is determined not by properties of hydrocarbons entering into the composition of fuels, but mainly by the presence in fuels of such substances as sulfur, sulfur compounds, water, naphthenic acids, etc.

In aircraft with turbojet and turboprop motors mainly aggregates and parts of fuel system of aircraft and motors manufactured from nonferrous metals and alloy steels are subjected to corroding action of fuel.

Different grades of jet propellants possess different corrosion aggressiveness.

Fuel T-1, prepared from low-sulfur oils, is practically unaggressive and does not cause corrosion of fuel system of engines.

Corrosion of alloys of metal noted in rare cases was caused chiefly by presence in fuel of free water.

Somewhat greater corrosion aggressiveness is possessed by fuels TS-1 and T-2, prepared from sulfur crudes of Volga region.

Chemical composition of sulfur compounds contained in commercial grades of jet propellants TS-1 and T-2, is listed in Table 40.

Table 40. Chemical Composition of Sulfur Compounds Contained in Jet Propellants TS-1 and T-2 (According to Ya. B. Chertkov and V. N. Zrelov)

Fuel	Content of sulfur compounds, %					
	Total sulfur	Elemental sulfur	Mercaptans	Disulfides	Sulfides	Residual sulfur
TS-1	0,240	Absence	0,004	0,051	0,032	0,153
T-2	0,220	"	0,005	0,009	0,015	0,191

Some sulfur compounds are especially aggressive with respect to copper and its alloys, with which they can enter into chemical reaction.

At increased temperatures the corrosion aggressiveness of sulfur compounds is intensified. Thus corrosion of bronze by fuels TS-1 and T-2 is increased 1.5-2.0 times with increase of temperature of fuels by 25°C (from 95 to 120°C) [19].

Externally corrosion of aggregates and parts of fuel system appears in darkening and appearance of dark brown or gray deposits or in uniform chemical corrosion of surface of metal.

Sometimes in fuel brown flakes are formed, consisting of iron hydroxide. These flakes can clog fuel filters, and also block plunger couples of fuel pumps.

Cases are known when corrosion is so strong that it causes destruction of coverings (cadmium) and even disturbance of work of separate aggregates (pumps).

In process of operation it was established that surfaces of metal washed by fuel are subjected to the strongest corrosion. Flow of fuel washes off protective corrosion deposits from metallic surfaces

and bares anew pure metallic surface, which is subjected to further corrosion.

Corrosion Properties of Sulfur and Its Compounds

From the entire variety of sulfur compounds which can be in jet propellants the greatest corrosion aggressiveness belongs to hydrogen sulfide, elemental sulfur and mercaptans.

Hydrogen sulfide causes strong corrosion of zinc, iron, copper, brass, aluminum and other metals with formation of sulfides of these metals.

With content of 0.0005% hydrogen sulfide in fuel corrosion of copper plate is observed. Traces of corrosion of copper plate are observed with concentration in fuel of 0.0003% hydrogen sulfide [23].

It is considered that for full safety there should be no hydrogen sulfide fuels.

Influence of presence of hydrogen sulfide in fuels on corrosion of copper plate can be seen from the following data:

Content of hydrogen sulfide in fuels, %	Test for corrosion of copper plate
0.0017	Presence of corrosion
0.0010	The same
0.0008	"
0.0005	"
0.0003	Traces of corrosion
0.0002	Absence of corrosion
0.0001	The same

Elemental sulfur possesses also high corrosion aggressiveness, intensely acting on copper and its alloys.

Influence of content of elemental sulfur in fuels (during absence in them of mercaptans) on corrosion of copper plate is listed below.

Content of elemental sulfur in fuels, %	Test for corrosion of copper plate
0.088	There is corrosion
0.010	The same
0.005	Traces of corrosion
0.001	No corrosion

In presence of mercaptans corrosion aggressiveness of elemental sulfur is sharply increased. It was established [23] that if in the fuel mercaptans are present, then corrosion of copper plate is observed with content of 0.001% elemental sulfur (Table 41). Therefore authors [23] consider that in the presence in fuel of mercaptans the permissible concentration of elemental sulfur should be below 0.001%.

Table 41. Influence of Content of Mercaptans and Elemental Sulfur in Fuels on Corrosion of Copper Plate

Content of elemental sulfur, %	Content in fuels of mercaptans, %	Test for copper plate
0,080	0,080	Corrosion
0,080	0,160	»
0,005	0,010	»
0,001	0,001	»

During action of mercaptans on bronzes (copper), zinc and cadmium complicated chemical compounds are formed, which are badly dissolved in fuel and form viscous (sticky) tarry deposits. Such products of corrosion can be precipitated on different parts of fuel system of engine, for instance on grid of filter, in cavity of burners, on valve of maximum turns, etc., and disturb its normal work.

Experience of operation of foreign countries shows that for complete removal of danger of corrosion of fuel system content of mercaptans in jet propellant does not have to exceed 0.005%, and in some cases it should not be more than 0.001%.

Corrosion of metals of fuel system of engines by active sulfur compounds and water in many cases is accompanied by formation of various kinds of compounds and deposits, which also present great danger for operation. Influence of mercaptan sulfur contained in fuel TS-1 on corrosion of copper is listed below.

Content of mercaptan in fuel, %	0.001	0.005	0.015	0.025	0.045
Corrosion of copper at 120°C, g/m^2	0.4	0.4	1.5	1.8	3.1

Thus, elemental sulfur, entering into reaction with copper, forms copper sulfides, which in the form of thin film cover the surface of parts. Sulfide film is insufficiently durable: being detached from the surface, it will form insoluble deposits in fuel.

Water and fuel with water content exert a corroding influence chiefly on steel parts of fuel system: water in most cases does not cause corrosion of nonferrous metals.

In conditions of operation for removal of corrosion and prevention of formation of deposits in fuel system of engine it is necessary regularly to check the quality of fuel entering into servicing of aircraft.

Content of active sulfur compounds is checked qualitatively by test for corrosion of copper plate, quantitatively it is determined by content in fuels of mercaptans. Fuels not corresponding to norms of standard, are not allowed for operation.

Content of Sulfur and Sulfur Compounds in Jet Fuels According to Specifications

For removal of corrosion aggressiveness of jet propellants the content of sulfur in fuels is strictly limited by standards.

Permissible content of sulfur and sulfur compounds in different grades of jet propellants is given in Table 42.

Actual content of sulfur and mercaptans in different grades of commercial samples of jet propellants of foreign countries is listed in Table 43.

Table 42. Content of Sulfur and Sulfur Compounds in Jet Propellants

Fuel	General content of sulfur, wt. %		Content of mercaptan sulfur, wt. %	
	according to specification	according to analysis	according to specification	according to analysis
ATK	0,20	0,079	0,005	0,0009
JP-1	0,20	0,035	0,005	0,0008
JP-3	0,40	0,350	0,005	0,005
JP-4	0,40	0,119	0,001	0,0017
JP-5	0,40	0,330	0,003	0,003

Table 43. Content of Sulfur and Mercaptans in Jet Propellants

Country	Fuel	Specification	Content of sulfur, % not more than	Content of mercaptan sulfur, % not more than
Soviet Union	T-1	GOST 10227-62	0,10	—
	TS-1		0,25	0,005
	T-2		0,25	0,005
England	Avtour-40	DERD-2482	0,20	0,005
	JP-4	DERD-2486	0,40	0,001
	Avtour-50	DERD-2494	0,20	0,001
	JP-5	DERD-2498	0,40	0,001
Canada	Avtour-50	3-GP-23c	0,20	—
	JP-4	3-GP-22c	0,40	0,001
France	Avtour-40	Air-3405	0,20	0,005
	JP-4	Air-3407	0,40	0,005
	JP-5	Air-3404	0,40	0,005
The United States (military fuels)	JP-3	MIL-J-5624E	0,40	0,005
	JP-4	MIL-J-5624E	0,40	0,001
	JP-5	MIL-J-5624E	0,40	0,001
	JP-6	MIL-F-25655	0,40	0,001
The United States (civil fuels)	Type-A (Avtour-40)	ASTM-D-2	0,30	0,003
	Type-B (JP-4)	ASTM-D-2	0,30	0,003
	Type-A-1 (Avtour-50)	ASTM-D-2	0,30	0,003

Naphthenic Acids and Naphthenic Soaps

Experiments established that in some cases in jet propellants of type of aviation kerosene there are contained traces of naphthenic acids. Naphthenic acids are very weak; therefore during determination

of the acidity of fuel by the usual methods they are sometimes not detected at all.

Naphthenic acids are capable of entering into a reaction with some metals of pipelines, and also with cadmium coverings of aircraft fuel systems. In some cases as a result of the interaction of naphthenic acids with metals products are formed which are insoluble in fuels, the products, deposited on filters, clog them and thus disturb the work of fuel system of aircraft.

Entry into jet propellant of soaps of naphthenic acids is impermissible, since they do not pass through pores of aircraft filters of fine purification; plugging of filters causes disturbance of fuel feed to the engine.

Soaps of naphthenic acids are deposited on surface of filter in the form of brown slimy deposit, which is easily distinguished from tarry substances, since soaps are dissolved in hot water and give alkaline reaction.

It is necessary to note that naphthenic acids and their soaps get in jet propellants only due to disturbance of technology of production; therefore the indicated phenomena are met very rarely.

Vanadium Corrosion of Metals

Microimpurities of vanadium in jet propellants in some cases may cause corrosion of heat-resistant alloys of combustion chamber of gas turbine engines. Vanadium enters into the composition mainly of high-molecular-weight nitrogen-containing compounds, which, as a rule, are concentrated in high-boiling petroleum fractions. During purification the main mass of compounds leaves the fuel, however even very small amount of vanadium remaining in fuel can be cause of burnout of heat-resistant alloys of combustion chamber. Mechanism

of burnout apparently, can be explained in the following manner.

During combustion of fuel vanadium in it changes into vanadium pentoxide (V_2O_5), having melting point of 685°C; in liquid form it is precipitated on walls of chamber. Inasmuch as in high temperature conditions vanadium possesses variable valence, it easily returns part of the oxygen to iron, which is destroyed with this, forming ferric oxide; vanadium pentoxide changes into tetroxide (V_2O_4). With surplus of oxygen in chamber vanadium tetroxide easily changes back to pentoxide.

Thus, vanadium can play role of carrier of oxygen and thereby cause intense corrosion even of heat-resistant alloys.

It is noticed that insignificant content in fuel of sodium oxide or sodium sulfate significantly strengthens vanadium corrosion of iron and its alloys.

Vanadium is contained mainly in residue of crude (black oil), partially in heavy fractions of crude and in some cases in kerosene.

In low-tar and low-sulfur Azerbaijan crudes (Balakhany, Kara-Chukhur, and Buzovna) the content of Vanadium amounts to 0.03-0.20%, considering ashes; in conversion to crude this will amount to approximately $6 \cdot 10^{-5}$%. In Groznyy and Dagestan area crudes the average content of vanadium amounts to $1-8 \cdot 10^{-5}$%, in crudes of Turkmen deposits $-2-3 \cdot 10^{-5}$%. In Ural-Volzhskiy area crudes the content of vanadium is 100-1000 times greater than in crudes of Groznyy region.

In cracking black oils, obtained from eastern oils, content of vanadium reaches $10-12 \cdot 10^{-3}$%, in black oil of direct distillation it is 3 times lower and amounts to $3-4 \cdot 10^{-3}$% [24].

In black oil of direct distillation from Tuymazy crude the content of vanadium reaches $2 \cdot 10^{-3}$% [25].

11. PLUGGING OF AIRCRAFT FILTERS

From the moment of entering into operation of aircraft with gas turbine engines, which fly at a speed of 700-1000 km/hr at an altitude of the order of 8000-10,000 m, the number of cases of disturbance of fuel feed to the engine due to complete or partial plugging of aircraft filters increased significantly.

In most cases the cause of plugging of filters is increased content in fuels of mechanical impurities, tarry substances and in some cases entry into fuel of soaps of naphthenic acids.

At the contemporary level of automation, used in fuel system of aircraft, it becomes especially necessary to fill the aircraft with fuel maximally free from hard particles. Already at present filters have been created for filtration of jet propellants which completely exclude the presence in fuel of particles with a dimension more than 5 μ.

Usually before servicing aircraft fuel is filtered through stationary filters and through filters of refueling units. When filter of refueling unit in thickness is not inferior to filter fixed in fuel system of aircraft, the aircraft filter should have only emergency value. It is natural to assume that such a filter can work during the whole time of work of the motor without clogging. In reality this is not so. Under the influence of some fuel components

Elements	FS Filters	Filters of aircraft
Carbon	8,36	21,55
Hydrogen	2,43	3,48
Nitrogen	0,37	0,61
Sulfur	0,83	0,54
Ash elements	46,16	44,07
Oxygen	42,05	29,75
In all	100	100

Composition of ash	FS Filters	Filters of aircraft
Iron	30,0	3,10
Copper	1,0	11,0
Tin	0,3—1,0	10,0
Cadmium	1—3	5—10
Zinc	20—30	1—3
Silicon	3—6	4,0
Aluminum	0,3	3,0
Sodium	0,4—1,0	3—10
Calcium	0,3	3—10
Magnesium	0,1—0,3	1—3
Chromium	—	1,0
Nickel	—	0,3—1,0
Lead	0,4—1,0	1,0

and hard particles in it complicated processes occur directly in the fuel system of aircraft, which lead to development or shaping of bigger particles, causing clogging of pores of aircraft filters.

Substances contained in fuels, which promote the formation of deposits on filters, include not only impurities of inorganic origin, but also the high-molecular-weight part of nonhydrocarbon organic compounds.

The composition of deposits which were formed after 100 hr of work on filter fixed on jet aircraft, during work on standard fuel TS-1 was investigated [26]. The composition of deposits formed on filters of refueling units was studied simultaneously (see Table 61).

Above is listed the composition of deposits (in wt.%) formed on filters during work on fuel TS-1:

With this the temperature of fuel in system of aircraft did not exceed 50°C, and in the refueling system it corresponded to ambient temperature in period of operation.

Research showed that deposits accumulated on filters of transport aircraft contain much ash (70-80%), ash elements (44-57%) and oxygen (27-42%). Oxygen in deposits on filters of refueling system was incomparably more than in deposits on filters of fuel system of aircraft. These deposits are distirguished also by composition of ash elements. Deposits on filters of refueling system consist mainly of iron and zinc. These elements are present chiefly in the form of oxides (for

zinc – hydroxides); therefore the content of oxygen in them is so great. Source of these elements are products of corrosion of iron pipelines and containers, in which there was fuel, and galvanized coverings. Furthermore, on filter of refueling unit a significant amount of silicon is observed, which is caused by dustiness of fuel during its storage and transportation.

Somewhat different is the composition of ash part of deposits removed from aircraft filters. Inasmuch as in this case the thickness of aircraft filters and filters of refueling units is identical, it is natural to consider that among the particles stopped by aircraft filters there must appear products whose appearance is caused by operational conditions directly in aircraft. In this case among ash elements on aircraft filter iron was detected significantly less than on filters of refueling unit, and incomparably more copper, tin, cadmium, sodium, calcium, and magnesium appeared. Obviously, ash part of deposits on filters of aircraft is composed of products of corrosion of metals of fuel system of aircraft and engine, among which in the first place should be put alloys of copper, cadmium coverings and alloys containing tin. Iron is detected comparatively little.

It was noticed that with increase of thickness of aircraft filter the content of iron (in the form of oxide) is increased in inorganic part of products clogging the pores of filter. This is explained by the fact that due to small dimensions particles of ferric oxide easily pass through 40-micron filter and are held back by 10-micron filter. In known measure zinc, aluminum, magnesium, and much silicon (as a result of penetration of dust into system pass into deposits). Presence of sodium should not be explained only by the presence of residual alkali in fuel, which can be only with bad washing later

on after alkalizing of it in factory.

Deposits formed on filters of refueling units and aircraft consist of 70-80% ash elements, representing a mixture of different oxides, complex structures and compounds of sulfur. Ash part of deposits consists of products of corrosion of containers, and also products of destruction mainly of nonferrous metals of fuel system of aircraft. In all cases significant place is occupied by contamination of fuel by dust.

On filters of refueling unit organic part of deposits is very small. It is increased on aircraft filters where the temperature is higher and where intense aeration of fuel during pumping, which occurs in contact with nonferrous metals (including copper), leads to more intense formation of tarry substances deposited on filter.

In all cases the comparatively large content of sulfur, nitrogen and oxygen in deposits formed on filters attracts attention. This indicates the fact that source of formation of organic part of deposits first of all is nonhydrocarbon part of fuel. Corrosion processes of nonferrous and ferrous metals in significant measure also can be explained by presence in fuel of nonhydrocarbon impurities. Process of packing of nonhydrocarbon part contained in fuel, carries oxidizing character, in spite of comparatively low temperatures. This is indicated by large content of oxygen in deposits. Apparently, with temperature are connected speed and depth of transformation of nonhydrocarbon compounds in solid substances. Therefore at lower temperature composition of deposits on filter will be characterized by smaller content of tarry compounds of organic character. With increase of temperature of fuel, at which it is in system of aircraft, quantity of such deposits will increase.

The better fuel is purified from unstable hydrocarbon and non-

hydrocarbon impurities, the less tarry deposits will be formed and, consequently, the less will clog the filter.

On formation of deposits on filters ash and organic substances are a mutual influence. Ash elements play role of centers, which are united by viscous organic compounds to formation of frame lattice. Such a lattice is packed and is enlarged up to particles whose dimension exceeds the dimension of holes of filtering element.

More complete extraction from fuel of products of corrosion, contaminations and other ash elements will permit to limit or to prevent process of enlargement of particles of products of oxidation of nonhydrocarbon components of fuel, retaining them in fuel solution or in the form of collodial system, which is characterized by dimension of particle less than 1 μ.

In connection with what has been said above it is necessary to retain fuel in hermetic reservoirs having anticorrosive coverings, and to ensure such filtration of it before servicing of transport aircraft with which mechanical impurities with dimension of particles more than 5 μ completely depart.

Plugging of Aircraft Filters in Time of Winter Operation

In practice of operation the cause of plugging of filters in winter time is considered the appearance of ice crystals. However many year experience of operation and recent research showed that disturbance of fuel feed to engine in many cases is caused by plugging of pores of filters not by ice crystals, but by film formed on filter, which consists of tarry substances associated with drops of water liberated during cooling of fuel.

If through filter "dry" fuel is pumped, i.e., fuel in which dispersed water is absent, it will freely pass through filter even when on grid of filter small deposits of mechanical impurities and

tar-carbon products are formed. But if through filter passes fuel with content of dispersed water, for instance, appearing as a result of settling of dissolved water during cooling of fuel, then drops will rapidly be associated with tar-carbon substances; as a result dense film can be formed which will cause plugging of pores of filter, and fuel feed to engine will be disturbed.

Thus, during operation of aircraft, when during prolonged high-altitude flights fuel in tanks of aircraft is significantly cooled. As a result of which dissolved water separates, danger of plugging of filters of fine purification can be created not only by ice crystals which is also completely possible, but also by products of association of tarry substances deposited on filter with microdrops of water separated from fuel during its cooling.

For removal of danger of plugging of filters of aircraft with tarry carbon substances those very chemical methods (additions), which are used for preventing of plugging of filters with ice crystals are completely acceptable. But in this case additions, being mixed with dissolved water, prevent its isolation from solution and thereby plugging of filters.

12. HIGH-ALTITUDE CHARACTERISTICS OF JET FUELS

High-altitude characteristics of jet propellants are conditionally called those properties of fuels which render influence on work of fuel system of aircraft at a great height. The most important of them are pressure of saturated vapors, boiling of fuel, and also its volatility, which determines losses of fuel from tanks of aircraft during climb and prolonged flights.

"Boiling" of Fuels in Aircraft Tanks During High Flights

Term "boiling" of fuel conditionally is called relatively violent separation from fuel of bubbles of vapor and dissolved air with decrease of external atmospheric pressure. If dissolved air separates from fuel gradually, with lowering of external atmospheric pressure, then violent separation of bubbles of fuel vapors appears only if pressure of fuel vapors is equal to or higher than external atmospheric pressure.

Gas turbine engines can effectively work on gasolines, ligroins, kerosenes and on their mixtures. However requirements for fractional composition of fuels are determined not only by specific requirements of engine, but also by conditions of their operation.

During flights higher than 12,000-14,000 m work of fuel system of aircraft without use of excess pressure in fuel tanks is reliable

only on fuels of type of aviation kerosene, evaporating within limits of 140-280°C and having pressure of saturated vapors lower than 50 mm Hg.

Jet propellants of wide fractional composition, evaporating within limits of 60-280°C at pressure of vapors of 100-150 mm Hg, ensure reliable work of fuel system of aircraft without use of excess pressure in fuel tanks only to height of 10,000-12,000 m.

Influence of Pressure of Fuel Vapors on Appearance of Boiling

By pressure of vapors of jet propellants to a significant degree is determined the reliability of work of fuel system of aircraft at a great altitude. From this point of view the limiting height of aircraft is that at which "boiling" of fuel appears, disturbing normal work of fuel system of aircraft. Danger of "boiling" and violent evaporation of fuel connected with this consists in the fact that vapors formed in feeding pipeline are able to disturb fuel feed to the engine.

Local resistances in fuel system of aircraft (joints, sharp turns and so forth) create local acceleration of flow, which leads to local pressure drop in the system. Due to local pressure drop in the fuel main line is possible not only evaporation of fuel, but also separation of dissolved air. And since fuel vapors and separated air formed in fuel main line can not be removed, accumulation of them will form vapor plugs, able to cause braking of flow in pipeline and thereby to lead to very serious and dangerous disturbances of work of fuel system.

Pressure of Vapors of Jet Fuels

Pressure of saturated vapors of jet propellants – is a variable magnitude and depends on its fractional composition and temperature. As a rule, the lighter the fractional composition of fuel, the higher the pressure of its vapors. With increase of temperature pressure of vapors of jet propellants is increased (Table 44).

Table 44. Pressure of Saturated Vapors of Jet Propellants

Temperature of fuel °C	Pressure of saturated vapors, mm Hg			
	T-2	TS-1	T-1	T-6
0	25	15	10	5
20	40	20	15	10
38	85	35	25	15
60	160	45	35	20
80	280	80	65	30
100	470	150	130	50
120	700	280	220	75
140	1100	480	400	130
160	1600	800	630	200
180	—	1200	1000	340
200	—	1800	1600	660

Pressure of saturated vapors of jet propellants of foreign countries practically differs little from pressure of vapors of native types of jet propellants.

Density of Saturated Vapors of Jet Fuel

Density of saturated vapors is called the quantity of fuel in unit of volume of gas space above surface of liquid, and is measured in g/cm^3. It was determined that the higher the temperature and pressure of saturated fuel vapors, the greater their density (Table 45).

Table 45. Density of Saturated Vapors of Jet Propellants T-1 [3]

Temperature of fuel, °C	Pressure of saturated vapors, mm Hg	Density of saturated vapors $\gamma \cdot 10^3$, g/cm^3	Temperature of fuel, °C	Pressure of saturated vapors, mm Hg	Density of saturated vapors $\gamma \cdot 10^3$, g/cm^3
85	82	0,435	150	551	2,695
107	150	0,834	152	581	2,837
129	300	1,525	160	708	3,425
139	404	2,018	164	784	3,776
146	494	2,427			

Altitude at which fuel starts to "boil" is in direct dependence on pressure of fuel vapors and on temperature. The higher the pressure of fuel vapors, the lesser the height at which fuel starts to "boil" in tanks of aircraft (Fig. 20).

From Fig. 20 it is clear that if tanks of aircraft are filled with fuel at 20°C with pressure of vapors of 60 mm Hg, then it will "boil" at altitude of 19,000 m. But if at the same temperature fuel is poured with pressure of vapors 140 mm Hg, then this fuel boils at an altitude of 14,500 m. Starting aviation gasoline B-70 with pressure of vapors 280 mm Hg at 20°C will "boil" at an altitude of 10,500 m.

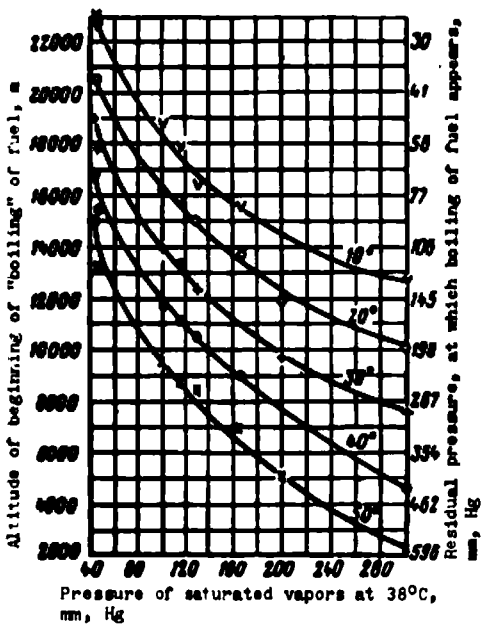

Altitude of beginning of "boiling" of fuel, m
Residual pressure, at which boiling of fuel appears, Hg
Pressure of saturated vapors at 38°C, mm, Hg

Fig. 20. Appearance of "boiling" of fuels in tanks of aircraft depending on temperature and pressure of vapors of jet propellants.

Solubility of Gases in Fuels Depending on Pressure and Temperature

Research conducted in laboratories of "Sun Oil Co." by the order of the United States Air Force, permitted to establish certain general rules of solubility of nitrogen, oxygen and carbon dioxide in jet propellants.

Eight samples of fuels were investigated which has the following characteristics. Density of fuels oscillated within limits 0.760-0.800 g/cm^3, content of aromatic amounted to from 4.0 to 14.4%. Molecular weight oscillated from 121 to 156.

As a result of conducted research the following was established [27].

At constant pressure with increase of temperature the solubility of nitrogen, oxygen and air in fuel decreases. With increase of temperature to 204°C solubility of carbon dioxide decreases, at

temperatures higher than 204°C it is somewhat increased.

Solubility of oxygen in fuels was studied to a temperature of 150°C. At temperatures higher than 150°C oxygen starts to enter into reaction with fuel, and it was difficult to judge its real solubility.

With increase of pressure the solubility of nitrogen, oxygen and carbon dioxide in fuels is increased.

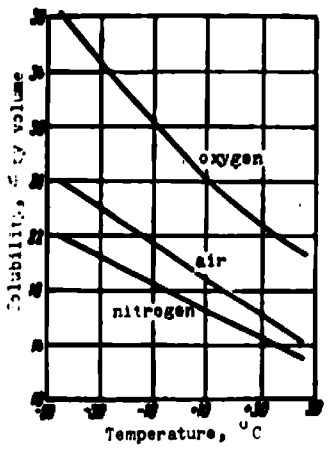


Fig. 21. Solubility of gases in jet fuel JP-4 at different temperatures and atmospheric pressure.

Solubility of air, nitrogen, oxygen and carbon dioxide in aviation kerosenes of type JP-5 and ATK is lower than in fuel JP-4. At identical temperature and pressure the solubility of oxygen in jet propellants is higher than solubility of nitrogen (Fig. 21).

Yield of Dissolved Air From Fuel

During climb of aircraft in altitude, when external atmospheric pressure drops, from fuel air dissolved in it starts to separate (Table 46).

From data of Table 46 it is clear that if initial content of dissolved air in fuel of type of aviation kerosene ATK amounted to 11.5%, then during climb to altitude of 10,000 m (external pressure 300 mm) from fuel 8.5% air separated and in fuel there remains only 3%. This means that if in tanks of aircraft there was 30,000 liters of aviation kerosene, from it could separate up to 2550 liters of air to limit of fuel saturated with vapors.

Together with air from tanks fuel vapors will depart also, which partially causes losses of it.

Table 46. Yield of Air Dissolved in Jet Propellants During Climb in Altitude

External pressure during rise in altitude, mm Hg	Content of air in fuels, % by volume		External pressure during rise in altitude, mm Hg	Content of air in fuels, % by volume	
	aviation kerosene ATK	fuel JP-4		aviation kerosene ATK	fuel JP-4
700	11,5	18,5	400	6,0	10,0
700	10,5	17,5	300	4,5	8,0
600	9,0	15,0	200	3,0	5,0
500	7,5	12,5	100	1,8	2,5

Losses of fuel from tanks of aircraft shaprly increase with increase of pressure of fuel vapors poured into tanks. This dependence is shown in Table 47. It is necessary to consider that with increase of temperature the pressure of fuel vapors is increased.

Table 47. Influence of Pressure of Fuel Vapors on Magnitude of Losses During Climb to Altitude of 18,277 m

Fuel	Pressure of fuel vapors at 38°C mm Hg	Losses of fuel, wt % at initial temperature of fuel	
		15,5° C	38° C
Aviation kerosene ATK.....	5	0	0
Wide fraction (type JP-4).....	105	0	1,0
Aviation gasoline heavy.....	258	7,5	16,5
Aviation gasoline light.....	334	10,5	19,5

During operation in winter conditions losses of fuel during flight can be decreased by fueling tanks of aircraft with cooled fuel.

To remove or to lower saturation of fuel with air during its storage is practically impossible; consequently, losses of fuel connected with yield of air from fuel during climb of aircraft to great altitude are inevitable if fuel tanks work without excess pressure. During work of fuel system under excess pressure these losses can be significantly lowered or completely removed.

Volatility at Low Pressure

With increase of temperature, evaporation of jet fuels is increased. Especially strongly is increased evaporation of fuels

from the surface during lowering of external atmospheric pressure, which is observed during flights of aircraft at a great altitude. In Table 48 are listed data about the evaporation of jet fuels at high temperatures and with different rarefaction of air [61].

Table 48. Evaporation of Jet Propellants at High Temperatures Depending on Rarefaction of Air (in %)

Indices	TS-1		T-1		T-5	
Altitude of flight, m.....	10 000	18 000	10 000	18 000	18 000	25 000
Residual pressure, mm Hg.....	198	56	198	56	56	—
Temperature of fuel, °C.....						
50	0,05	0,11	0,02	0,07	—	—
92	0,16	39,20	0,14	10,80	—	0,70
117	10,94	77,10	1,18	51,0	0,85	9,92

13. LOW-TEMPERATURE PROPERTIES OF JET FUELS

Low-temperature properties of jet propellants are determined by physicochemical indices which characterize the behavior of fuel at low temperatures. The most important low-temperature characteristics of jet propellants having value for operation are temperature of turbidity, temperature of beginning of crystallization (freezing), temperature of thickening and pumping and change of viscosity of fuel at low temperatures.

Cooling of Fuel During Storage

Cooling of fuel during storage in fuel storage tanks of airports depends on geographic location of region of storage and on time of year. In northern regions of Soviet Union the temperature of fuel in fuel tanks on ground during one year can oscillate within limits of ±40°C. In regions of extreme north in winter fuel can be cooled to temperature of -60°C. During storage in underground tanks the temperature of fuel in the same regions will oscillate in significantly narrower limits.

Thus, to guarantee normal operation when ground temperatures oscillate in very wide limits it is necessary that propellant does not freeze and remains efficient up to a temperature of -60°C.

Temperature of Turbidity

Temperature of turbidity of jet propellants called that temperature at which fuel in test condition starts to grow turbid. Turbidity of fuel, as a rule, is caused by separation from fuel of drops of dissolved water. According to old standards the temperature of turbidity of jet propellants T-1 and TS-1 was permitted not higher than -50°C. In new standard this index is not standardized.

Turbidity is a very important operational index of jet propellants, since it signals the presence of finely dispersed water.

In English and American practice it is considered that the presence in fuel of 0.003% of dispersed water gives light turbidity, observed visually.

Content in fuel of finely dispersed water less than 0.003% cannot be observed visually, since with this visible turbidity of fuel does not appear.

For servicing of aircraft it is prohibited to deliver fuel in which turbidity is visually noticed, since during cooling of such fuel to temperature below 0°C icing of filters can occur because of accumulation of free water separated from fuel on surface of filters.

Temperature of Beginning of Crystallization

Temperature of beginning of crystallization of jet propellants is called that maximum temperature at which in test conditions in fuel crystals of high-melting hydrocarbons are observed with naked eye.

In specifications of foreign countries, and also in earlier specifications of Soviet Union this constant was called the temperature of freezing, although determination was made practically by the same method.

According to existing standards the temperature of beginning of crystallization of jet propellants should be not higher than -60°C.

At the temperature of beginning of crystallization all kinds of propellants remain very fluid and are freely pumped with a pump.

Temperature of beginning of crystallization practically is that minimum temperature at which fuel passes easily through thin filters.

Temperature of Thickening and Pumping of Fuel

Temperature of thickening of fuels is called that temperature at which tested fuel in conditions of experiment thickens so that with slope of test tube with fuel at an angle of 45° the level of the product remains motionless (does not flow) for 1 min.

Temperature of thickening of jet propellants is not standardized, but practically jet propellants congeal and lose their fluidity at a temperature near -65°C.

Table 49. Temperature of Pumping of Jet Propellant of the Type of Aviation Kerosene ATK

Samples of fuel	Freezing point (beginning of crystallization), °C	Temperature of thickening, °C	Minimum temperature of pumping without mixing, °C
1	—46	—49	—56
2	—42	—46	—50
4	—45	—46	—50
5	—43	—47	—50
6	—43	—49	—51
8	—41	—43	—48
9	—45	—49	—51

At a temperature of thickening jet propellant becomes not fluid and it is difficult to pour or to pump it. Jet propellants congeal not at once; during cooling they gradually thicken, their viscosity is increased, and with further cooling they become very viscous and have little fluidity. However, if the thickened fuel is subjected to intense mixing, it again becomes fluid and it is possible to pour or pump it with a pump. But if fuel diluted by means of intense mixing remains quietly standing, then at the same temperature it again will thicken and will have little fluidity.

In Tortonian scientific research center special investigations were conducted on the establishment of minimum temperature of pumping of jet propellants of the type of aviation kerosenes. Results of these investigations are given in Table 49.

From Table 49 it is clear that the minimum temperature of pumping of fuel actually is close to the temperature of thickening, which is approximately 5-10°C lower than the freezing point.

Crystallization of Benzene in Fuels

In jet propellants of wide fractional composition from beginning of boiling near 60°C the presence of benzene is possible. Content of large amount of benzene in jet propellants is undesirable for the following reasons.

1. Benzene possesses high hygroscopicity and is able to dissolve water 10 times more than paraffin hydrocarbons.

2. In the presence in jet propellants of benzene in gas-turbine engines increased scale formation is observed.

3. Melting point of benzene is 5.4°C; therefore with strong cooling of fuel it will be crystallized.

The more benzene is contained in the fuel, the higher the temperature at which its crystallization starts (Table 50).

It is necessary to consider that if benzene is added together with other aromatic hydrocarbons to fuel of another chemical composition, then precipitation of crystals of benzene from gasoline will occur at several other temperatures, but general rule of crystallization of benzene in gasolines will be kept.

Danger of crystallization of benzene consists of the fact that with this homogeneity (uniformity) of fuel is disturbed, since benzene

passes into solid phase.

Even insignificant crystallization of benzene is undesirable and dangerous, since crystals of benzene can appear also as centers of crystallization of hydroscopic water.

Table 50. Crystallization of Benzene in Gasolines

Content of benzene in mixtures, % by volume.	Temperature of precipitation of crystals of benzene, °C	
	From isooctane	From gasoline, B-70
0	−65	−65
5	−60	−60
10	−48	−54
15	−38	−44
20	−31	−37
25	−26	−32

Crystallization of High-Melting Paraffins

In light gasoline fractions of crude, evaporating within limits of 40-200°C, high-molecular weight paraffin hydrocarbons having high melting point are practically absent; consequently, there is no danger of crystallization of paraffin in gasolines. Therefore gasolines having freezing points of -60°C can be obtained from almost all types of crudes.

Something completely different is observed in kerosene fractions of crude, evaporating within limits of 130-280°C, in which there can be contained high-molecular-weight paraffin hydrocarbons with high melting point. Such kerosenes, obtained from high-paraffin crudes, have high freezing point (-40°C), caused by crystallization of high-molecular-weight paraffin hydrocarbons contained in them.

As is known, paraffin hydrocarbons of normal structure, starting with hexadecane ($C_{16}H_{34}$), have melting point higher than 0°C; crystallization of such high-melting hydrocarbons in kerosene also determines loss of their mobility and freezing of fuel during cooling.

Presence in kerosene of significant amount of high-melting paraffi hydrocarbons causes crystallization of kerosene during its cooling.

Smallest crystals of paraffin, as also benzene, sometimes play the role of centers of crystallization of ice. Crystals of ice formed

lumps are also deposited in pores of filters and disturb fuel feed to engine.

For the indicated reasons in native (Soviet) aviation it is permitted to use aviation kerosenes with temperature of beginning of crystallization of -60°C.

Obtaining of kerosene with low temperature of beginning of crystallization is connected with certain difficulties. Such aviation kerosenes can be obtained only from crudes of naphthenic-paraffin base, in which high-melting paraffin hydrocarbons are absent.

Change of Viscosity of Fuels at Low Temperatures

Viscosity of jet propellants of the type of aviation kerosenes in all existing standards is standardized at a temperature from 20 to 40°C.

Viscosity of jet propellants at a temperature of 20°C according to standards is allowed for TS-1 not lower than 1.25 cs, for T-1 not lower than 1.50 cs. During work on fuels with lower viscosity increased wear of plunger pumps is observed. Viscosity at a temperature of -40°C according to standards is allowed for TS-1 not more than 8 cs, for T-1 not more than 16 cs.

In majority of specifications of foreign countries for jet propellants of type of aviation kerosenes the viscosity at positive temperatures is not standardized. At a temperature of -18°C viscosity is allowed not more than 6 cs (England) and at -40°C not more than 15 cs (the United States and Canada).

14. COOLING OF FUELS IN AIRCRAFT TANKS

Transport aircraft with turbojet and turboprop engines usually fly at an altitude of 7000-10,000 m, where temperature of surrounding air reaches -40 to -65°C.

Experiments established that during flights of aircraft at subsonic speed in zone of low temperatures fuel in the tanks of aircraft gradually cools. Depth and rate of cooling of fuel in tanks of aircraft during flight are unequal, on the basis of them the following factors are determined.

1. Initial temperature of fuel poured into tanks of aircraft; the higher the initial temperature of fuel, the stronger its cooling.

2. Temperature of surrounding air; the lower the temperature of surrounding air during flight, the stronger the cooling of fuel.

3. Duration of flight in zone of low temperatures; the more prolonged the flight, the stronger the cooling of fuel.

4. Type of fuel tanks. In metallic tanks fuel is cooled significantly more strongly than in soft rubberized tanks, due to lower heat conduction of walls of tanks.

By rate and depth of cooling of fuel in tanks of aircraft during flight to a significant degree is determined the selection of type of jet propellant and temperature of its crystallization.

Considering the importance for operation of depth and rate of cooling of fuel during prolonged flights, foreign aircraft-building firms conduct special tests for the purpose of determination of the rate and depth of cooling of fuel in tanks of transport aircraft with turbojet and turboprop motors. Tests showed that during prolonged transatlantic flights of Boeing-707 and Britannia aircraft in some cases temperature of fuel in tanks dropped to -37°C.

On the basis of obtained data of airline of the United States and Canada in 1960 operation of indicated aircraft on jet propellant ATK, having freezing point of -40°C was prohibited, and it was recommended for prolonged and transatlantic flights to use aviation kerosene ATK, having freezing point of -50°C, and in some cases fuel of wide fractional composition — JP-4, whose freezing point is -60°C.

Rate and depth of cooling of fuel in tanks of Comet-4, Boeing-707, and Britannia aircraft, which were determined during tests, are listed in Table 51.

Table 51. Cooling of Fuel in Tanks of Certain Foreign Aircraft During Flights

Duration of flight, hr	Comet-4 (altitude 10-12 km. Speed 750-800 km/hr)		Boeing-707 (altitude 10-12 km Speed 800-900 km/hr)		Britannia (altitude 7-8 km. Speed 550-650 km/hr)		Comet-4 (altitude 10-12 km. Speed 750-800 km/hr)	
	Temperature of external air, °C	Temperature of fuel in tanks, °C	Temperature of external air, °C	Temperature of fuel in tanks, °C	Temperature of external air, °C	Temperature of internal surface of tanks, °C	Temperature of external air, °C	Temperature of fuel in feeding pipeline, °C
0 (on the ground)	15	15	15	10	—10	—1	10	10
0,5	—40	10	—50	—2	—32	—10	—30	0
1,0	—56	—15	—60	—15	—45	—30	—68	—5
1,5	—60	—20	—60	—20	—50	—36	—65	—10
2,0	—67	—30	—60	—22	—50	—36	—65	—20
2,5	—63	—30	—60	—24	—56	—36	—65	—20
3,0	—57	—28	—65	—26	—56	—38	—68	—22
3,5	—55	—27	—67	—28	—56	—41	—68	—24
4,0	—55	—26	—65	—28	—52	—40	—68	—25
4,5	—53	—26	—65	—28	—46	—40	—68	—25
5,0	—56	—28	—65	—28	—42	—36	—60	—24
5,5	—40	—28	—	—	—37	—32	—62	—24
6,0	—	—	—	—	—32	—26	—60	—26
6,5	—	—	—	—	—29	—23	—20	—20

Strong cooling of fuel in tanks of aircraft during prolonged flight in certain cases is dangerous, since it can lead to disturbance of normal fuel feed to motor.

Coefficient of Heat Conduction of Jet Fuels

Rate of cooling of fuel in tanks of aircraft at subsonic flight speeds or with speed of heating of fuel in tanks of aircraft at supersonic flight speeds will depend not only on difference of temperatures, but also on coefficient of heat conduction of fuels and walls of fuel tanks.

Works of A. V. Kozyukov [62] established that coefficient of heat conduction of different types of propellants is unequal. As a rule, with increase of density of fuel the coefficient of heat conduction decreases somewhat at low temperatures and is increased at temperatures higher than 50°C (Table 52).

Table 52. Coefficient of Heat Conduction of Liquid Jet Propellants at Various Temperatures

Temperature, °C	Coefficient of heat conduction of different kinds of fuels		
	T-1 (density 0.810 g/cm³)	T-5 (density 0.845 g/cm³)	R-70 (density 0.730 g/cm³)
−50	0,1090	0,1060	0,1130
0	0,1025	0,1020	0,1035
50	0,958	0,0968	0,0950
100	0,0896	0,0922	0,0864
150	0,0830	0,0878	0,0790
200	0,0766	0,0824	0,0688

Separation of Water From Fuel in Time of Flight of Aircraft

Amount of water which can be in the fuel in dissolved state depends on temperature of fuel and atmospheric humidity. The higher the temperature and atmospheric humidity, the more dissolved water can be in fuel. With decrease of temperature of fuel part of water dissolved in fuel separates out of the solution. If with this atmospheric humidity did not drop, then water separated from solution in the form of smallest drops will be in the beginning in suspension (dispersed water), and then drops of water will be consolidated and settle to

bottom of container.

If during separation of dissolved water from fuel the humidity of surrounding air significantly dropped, then separated drops of water will be evaporated, and only part of them will be precipitated on bottom of tanks of aircraft. With this the lower the humidity of of the surrounding air, the more water separating from the fuel will be evaporated.

In Table 53 are listed data on the separation of dissolved water from jet propellant during its cooling [30].

Table 53. Separation of Dissolved Water from Fuel

Fuel	Density of fuel g/cm³	Solubility of water in fuel, wt. %		Separation of water from fuel during cooling from 30 to 0°C, g/ton
		At 30°C	At 0°C	
Aviation gasoline....	0.710	0.0110	0.0022	88
Aviation kerosene ATK	0.795	0.0068	0.0016	72

V. Kasten [31] reports that in his experiments during cooling of 20 t of jet propellant from 10°C to -12°C around 1 liter of water was separated. Native [Soviet] fuels conduct themselves analogously. At a temperature of 20°C in fuel TS-1 is dissolved up to 0.0085% water during cooling of it to 0°C there remains around 0.0022% in dissolved form. Consequently, from every ton of fuel TS-1 during cooling of it from 20°C to 0°C 63 g of water is separated, and from 20 t of fuel — around 1260 g of water.

Thus, cooling of fuel in aircraft tanks during flight can create a number of difficulties, which always must be considered in operation.

15. WATER CONTENT OF JET FUELS

Water can be in jet propellants in free form, in the form of water-fuel emulsions or in dissolved state (hygroscopic).

Free water contained in fuel can be source and cause of formation of water-fuel emulsions and lead to complete saturation of fuel with hygroscopic water.

Presence of water in fuel in any form is undesirable and dangerous for operation. Getting into fuel system of the engine, water can freeze, disturb fuel feed to the engine and cause its stopping. Furthermore, water is one of the causes of corrosion of pumps, fuel leads and other parts and aggregates of the fuel system of aircraft.

Table 54. Methods of Determination of Water Content in Jet Propellants

Area of application of method	Method of determination	Essence of method	Water in fuel	Limits of accuracy of method
On flying field	Visual	Observation with naked eye of fuel poured into glass cylinder	Free and dispersed	Freely dispersed water can be observed with content not less than 0.003%
	Chemical	Fuel is collected with a syringe and passed through a water-sensitive capsule, or in fuel a water-sensitive capsule is immersed	Dispersed	With content in fuel of dispersed water not less than 0.003%

Table 54 continued

Area of application of method	Method of determination	Essence of method	Water in fuel	Limits of accuracy of method
On flying field	The same	Into fuel poured into glass cylinder, tablet of calcium bichromate or potassium permanganate is dropped	Only free	Water in fuel in the form of separate layer
	The same	Into fuel water-sensitive paper or paste applied on rod is lowered	The same	The same
In the laboratory	The same	Reaction of water in the fuel with calcium hydrate	Freely dispersed and dissolved	Up to 0.001%
	The same	Titrating of fuel with water content with pyridineacetyl-chloride	The same	Up to 0.0005%

Methods of determination of the water content in fuels are given in Table 54.

Free Water in Jet Fuels

Main cause of entry of water into refueling units and into tanks of aircraft is accumulation of water in stationary fuel containers of airports and storage places.

Despite the established opinion, removal of water from fuel is a far from simple problem. Therefore it is expedient to consider precisely this question somewhat in greater detail.

Water practically is not mixed in petroleum fuels and due to its greater density always settles on bottom of tank in the form of separate layer. But, if water in fuel is in finely atomized state, small drops of water are precipitated very slowly from fuel. Precipitation rate of finely dispersed water from fuel obeys the Stokes law;

it will be the less, the greater the density and viscosity of fuel and the less the dimension (diameter) of drops of water.

In kerosene very small drops of water are able for several hours to be in suspension; in highly viscous oils in the absence of their preheating finely dispersed water can be in suspension for many days and weeks. Thus, for complete removal of water from fuel its prolonged settling is necessary.

In England the following norms are accepted for duration of settling of jet propellants and aviation gasolines before conveying them from reservoirs for servicing of aircraft:

1. for jet propellants of the type of aviation kerosenes a duration of settling not less than 3 hr 20 min for each meter of height of layer of fuel in reservoir;

2. for aviation gasolines — not less than 50 min for each meter of height of layer of aviation gasoline in reservoir.

During settling of fuels with water content frequently a significant part of drops of finely dispersed water precipitating from fuel settles on rough surface and in seams of walls of tanks or other containers. It must be removed. In refueling units as a result of agitating of fuel during shipments water gathers in the settling tank, whence it also must be removed.

Good settling and complete removal of water from fuel are the most important measures for guarantee of normal and reliable work of engines.

Water-fuel Emulsions

Emulsion is the name for a mixture of two mutually insoluble liquids, in which one liquid is distributed in the other in the form

of finely broken up drops. Dimensions of these drops can be so small that they are not precipitated from the emulsion under the usual conditions or are precipitated only after prolonged period of settling.

In conditions of operation gasoline emulsions are met very rarely, but significantly more frequently kerosene emulsions are formed. In kerosene emulsions usually drops of water are distributed in kerosene. Such emulsions are called hydrophobic. In these emulsions water is the internal, dispersed phase, and fuel is the external, dispersion medium. Dimensions of water drops in such emulsions usually oscillate from 0.1 to 100 μ. Drops of water with bigger dimensions usually do not stay long in fuel or form unstable emulsions, which comparatively are easily destroyed during settling.

Fuel emulsions can be formed only during very intense mixing of fuel with water. The higher the degree of dispersion (breaking up) of water, the stabler the emulsions and the slower they are destroyed and separated into fuel and water. Content of water in fuel emulsions oscillates from fractions of percent to 60%.

Even with very strong mixing of aviation kerosene with water emulsions are not always formed, or unstable emulsions are formed which are destroyed relatively rapidly.

Cause of formation of stable fuel emulsions is the presence in fuels of tarry substances, naphthenic acids and their soaps. These substances possess some surface activity and are able to be absorbed on the interface of phases of the emulsion, i.e., on surface of water drops. "Protective" films (sufficiently durable) formed by them prevent merging of separate drops of water into bigger ones, and thereby destruction of emulsion and separation of drops of water from fuel lags.

Second cause of formation of stable emulsions is the appearance of charges of static electricity on drops and solid particles. Under the influence of charges analogous in sign charges drops and solid particles are repulsed from each other, which prevents their merging and the destruction of the emulsions.

Sufficiently stable aqueous emulsions of kerosene sometimes are observed in lower part of railroad cisterns transporting aviation kerosene.

It is most probable that one of the emulsifiers stabilizing water-kerosene emulsions is naphthenic acids.

For destruction of fuel emulsions it is necessary to destroy the protective films enveloping the drops of water, and to neutralize their electrical charges. After this under the influence of forces of mutual attraction small drops of water merge into bigger ones, and emulsion is destroyed.

In industry petroleum emulsions are destroyed by heating, settling of crude and addition of special substances — so-called de-emulsifiers.

In aviation in conditions of operation fuel emulsions are destroyed by prolonged settling of fuel with subsequent removal from it of separated water.

Causes of Accumulation of Water in Fuels During Storage

During storage of fuels in aircraft tanks and containers of fuel storage tanks, on the bottom of the container water is periodically accumulated. Therefore during operation it is recommended to conduct an observation and systematically to remove accumulated water from cisterns and fuel tanks of aircraft.

It is acceptable to consider that the source of appearance of water in tanks of aircraft and in fuel cisterns is condensation of

moisture from the air due to change of temperature (dew point). There are also cases when rain or ground water gets into fuel container or storage places.

Entry of water into aircraft fuel tanks and into stationary fuel containers as a result of condensation of moisture from air during change of temperature of external air is caused by the fact that in the air there is always contained a certain amount of water vapor. The higher the temperature, the more water vapor can be contained in air. Cooling of air inevitably causes condensation of part of the water vapor. For instance, at 10°C and with complete saturation in the air there can be contained 9.4 g/m^3 of water vapor; with decrease of temperature of air to 0°C from each cubic meter of this air 4.6 g of water precipitates.

Proceeding from what has been presented, it was possible to expect that more water will appear in a fuel container where there is a greater volume of free space not filled with fuel. However, if we take three fuel cisterns of equal volume and fill one of them with kerosene 75%, the second — 25%, and the third keep absolutely empty and leave these fuel cisterns to stand for several months, measuring the amount of accumulated water in each cistern, then the following will be observed. The greatest amount of water will be accumulated on the bottom of the first cistern, where there was less free air space and kerosene. In the third cistern, where there was absolutely no fuel, there will be no water, and in the second cistern, where 25% fuel was poured, water accumulated approximately 3 times less than in cistern filled with 75%.

Consequently, there exist other causes of the appearance and accumulation of water in tanks of aircraft and fuel containers.

Free water appears in fuels during their storage not only as a result of condensation of it from air, but also due to absorption by fuel of water from the air with its subsequent separation. In this case the mecnanism of accumulation of water in fuel containers will be the following.

Fuel absorbs water vapor from the air; with decrease of temperature of fuel the solubility of water in the latter decreases, excess water separates out of the solution and drops of this water settle on the bottom of the container or are evaporated.

Purification and Dehydration of Jet Fuels with the Help of Electrodeposition

Dehydration and desalting of crude oil with the help of electrodehydrators of different construction has been widely used in Soviet Union for many years.

Recently in foreign literature materials were published on the purification and dehydration of jet propellants issued for servicing of aircraft, with the help of electrodeposition.

Thus, it is indicated [32] that by electrodeposition very high degree of purification from mechanical impurities and water of jet propellant JP-5 is achieved before delivery of it for servicing of aircraft (Table 55).

Table 55. Results of Purification of Jet Propellant JP-5 by Electrodeposition

Products of contamination	Content, %	
	Up to purification	After purification
Sea water	3.0	0.00006
Finely dispersed ferric oxide ..	0.008	0.0005

However, as far as it is possible to judge by the literature, in airports of foreign countries the method of purification of jet propellants with the help of electrodeposition still has not found wide application.

16. HYGROSCOPICITY OF JET FUELS

Hygroscopicity of jet propellants is called the property of these fuels to absorb water vapor from the air. Water absorbed by fuel is called hygroscopic.

Hygroscopicity of Hydrocarbons

Hygroscopicity of hydrocarbons entering into the composition of aviation fuels is determined by their chemical structure and molecular weight.

Least hygroscopicity belongs to paraffin hydrocarbons, and the greatest to aromatic hydrocarbons. Naphthenic hydrocarbons by their hygroscopicity occupy middle position between paraffin and aromatic hydrocarbons.

For all classes of hydrocarbons independently of their chemical structure, with increase of molecular weight the hygroscopicity decreases. In accordance with this, fuels with low molecular weight (gasolines) as a rule possess somewhat greater hygroscopicity than fuels with higher molecular weight (kerosene).

Materials available in the literature on hygroscopicity of individual hydrocarbons are not always identical, and sometimes are also contradictory.

Different hygroscopicity of the same hydrocarbons, obtained by different investigations, obviously is explained first of all by the fact that at the same temperature, but with different relative atmospheric humidity, in hydrocarbons there is dissolved an unequal amount of water; furthermore, during the study of hygroscopicity of hydrocarbons researchers tried different methods of determination of moisture content in hydrocarbons.

In Table 56 are listed the average or the most frequently met in the literature data concerning the solubility of water in hydrocarbons of different classes.

Table 56. Influence of Chemical Structure of Substance on its Hygroscopicity

Class of compound	Compound	Formula	Solubility of water in wt. % at temperature, °C	
			10	20
Paraffin hydrocarbon	Isooctane..	C_8H_{18}	0.0037	0.0055
Naphthenic hydrocarbon	Cyclohexane	C_6H_{12}	0.0049	0.0087
Aromatic hydrocarbon	Benzene....	C_6H_6	0.0400	0.0570

Influence of molecular weight of hydrocarbons on their hygroscopicity can be followed most graphically on derivatives of benzene (Table 57).

Table 57. Influence of Molecular Weight of Hydrocarbons on Their Hygroscopicity

Hydrocarbons	Molecular weight	Solubility of water in wt. % at temperature, °C				
		5	10	14	30	40
Benzene.....	78	0,024	0,034	0,041	0,062	0,102
Toluene.....	92	—	0,020	0,034	0,053	0,070
Xylene.....	106	—	0,010	0,015	0,046	0,060
Alkyl benzene.....	120	0,011	0,014	—	0,018 (20)	0,023

From data in Table 57 it is clear that the higher the molecular weight, the lower the hygroscopicity of aromatic hydrocarbons.

Hygroscopicity of Aviation Kerosenes

Chemical composition of aviation kerosenes of direct distillation is unequal and depends on the kind of crude from which they were obtained, and on its fractional composition. Due to different chemical composition and different molecular weight kerosenes like gasolines, possess different hygroscopicity.

As a rule, the lower the molecular weight of aviation kerosene and the greater the content in it of aromatic hydrocarbons, the higher its hygroscopicity.

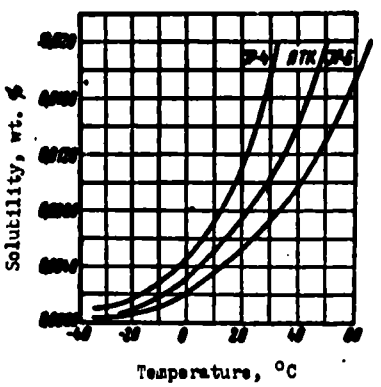


Fig. 22. Solubility of water in jet propellants of foreign countries.

Table 58. Hygroscopicity of Kerosenes (4)

Temperature, °C	Solubility of water, wt. %		
	In kerosene without aromatic	In aviation kerosene JP-5	In aviation kerosene ATK
—5	—	0,001	0,002
0	0,002	0,002	0,004
10	0,003	0,005	0,006
20	0,005	0,007	0,008
30	0,010	0,010	0,012
40	0,015	0,016	0,018

In table 58 are listed data of hygroscopicity of three kinds of kerosene of different chemical and fractional composition.

Hygroscopicity of different kinds of propellants is given in Fig. 22.

Reversible and Irreversible Hygroscopicity of Fuels

Water absorbed by liquid or solid matter is held with great force. In many cases removal of hygroscopic moisture from liquid or

solid matter presents a great difficulty.

Conducted works [29] showed that two forms of hygroscopicity of liquids can exist: a) irreversible hygroscopicity, and b) reversible hygroscopicity.

As is known, ethyl alcohol possesses high hygroscopicity. During storage in open container alcohol rapidly absorbs moisture from air. With absorption of moisture the alcohol is diluted, and its strength drops. Practically this process will continue, while content of alcohol in solution will not be lowered to very small concentration. In other words, alcohol accumulates the absorbed moisture, binds and almost does not liberate it spontaneously during changes of temperature and atmospheric humidity. During strong cooling such a solution gradually thickens, then freezes. Such a type of hygroscopicity of liquids we conditionally called irreversible, since water absorbed by liquid during change of temperature and atmospheric humidity practically does not separate back out.

Petroleum fuels not only absorb and dissolve moisture in themselves, but liberate it with decrease of temperature and atmospheric humidity. With change of temperature and humidity of ~~air,~~ the process of absorption or separation of moisture from petroleum fuel proceeds. This form of hygroscopicity of petroleum fuels we conditionally called reversible hygroscopicity.

Accumulation in propellants of free water, and also formation in them of crystals of ice and hoarfrost on walls of reservoirs and fuel tanks are caused by the reversible form of hygroscopicity of petroleum fuels.

Reversible form of hygroscopicity of petroleum fuels is the key to explanation of processes of water accumulation and formation

of crystals of ice in propellants.

Position of Hygroscopic Water in Liquids

Form of hygroscopicity of liquids is determined by the position of hygroscopic water in liquid.

During mixing of alcohol with water the volume of alcohol-water solution turns out to be somewhat less than the sum of volumes of water and alcohol taken on mixing.

A somewhat different phenomenon is observed during water accumulation or during absorption of moisture from air by petroleum fuels.

Molecules of water have small molecular volume and great dipole moment. These molecules are strongly associated with other molecules of water due to their ability to form hydrogen bonds. All hydrocarbons entering into the composition of propellants have significantly greater molecular volume than water. Molecules of hydrocarbons, as a rule, are nonpolar, and C-H bonds are incapable of forming hydrogen bonds with molecules of water. Attractive forces between molecules of water and hydrocarbons are very small, in consequence of which very small solubility of water in the majority of hydrocarbons and petroleum fuels is also observed.

Of all the hydrocarbons entering into the composition of aviation gasolines and jet propellants, benzene dissolves water best of all. For example, at 25°C the concentration of dissolved water in benzene, expressed in molecular fractions, reaches values 2.9×10^{3}, i.e., one molecule of water was apportioned to 350 molecules of benzene. But also with these concentrations molecules of water dissolved in benzene remain unassociated. Therefore it is considered that water dissolved in any hydrocarbon or in hydrocarbon fuel is in the form of

separate molecules. Precisely due to this petroleum fuels possess reversible hygroscopicity.

Evaporation and Separation of Hygroscopic Water from Fuel in the Form of Drops

With constant atmospheric humidity, when temperature sharply drops due to change of solubility of water in fuels, excess moisture separates from them in the form of finely dispersed drops, which in the beginning are in supercooled state, but then under the influence of intense mixing or lowering of temperature freeze and are turned into smallest crystals of ice.

At constant temperature or with its insignificant change, when atmospheric humidity is lower than 100% relative humidity, evaporation of hygroscopic moisture from fuel occurs. Moisture is evaporated from fuel as long as certain equilibrium is not reached between concentration of moisture in fuel and concentration of water in air.

Concentration of Moisture on Surface of Fuel

Condensation of moisture from the air due to lowering of temperature occurs not only on metallic walls of reservoirs and fuel tanks, but also on surface of cooled fuel. Where upon the moisture condensed on surface of the fuel does not freeze immediately, and in the beginning is dissolved, or spreads in the fuel in the form of drops. Its gradual turbidity begins; wave of turbidity slowly spreads down from above through the volume of fuel. With increase of concentration of moisture in fuel and lowering of its temperature, turbidity of fuel is strengthened.

For a certain interval of time, when moisture in fuel is strongly cooled, process of formation of small crystals of ice begins.

Influence of Density of Fuel on Solubility of Water

With increase of density of fuel the solubility of water in it drops. Consequently, with identical conditions in aviation gasolines more water can be dissolved than in aviation kerosenes (Fig. 23). However crystal formation became a serious problem namely after kerosenes began to be used in aviation, although in them less water is dissolved than in aviation gasolines. At first glance this looks paradoxical, but if the given question is considered somewhat more deeply, a clear rule can be established.

Process of crystal formation precedes separation from fuel of dissolved water in the form of smallest drops, and in aviation gasolines having small density and viscosity, the formed drops of water settle faster to the bottom of the container or are evaporated. In aviation kerosenes which have high density and viscosity, drops of water separated from solution will settle 4-5 times more slowly than in airplane gasolines, and therefore in the process of precipitation will freeze with formation of smallest crystals of ice. Danger of crystal formation in aviation kerosenes is increased also because jet aircraft (as distinguished from piston) fly at greater altitudes and in the zone of low temperatures; due to this, fuel is intensely cooled in aircraft tanks, which accelerates separation of water from solution and formation of supercooled drops of water, and then also of crystals of ice in fuels.

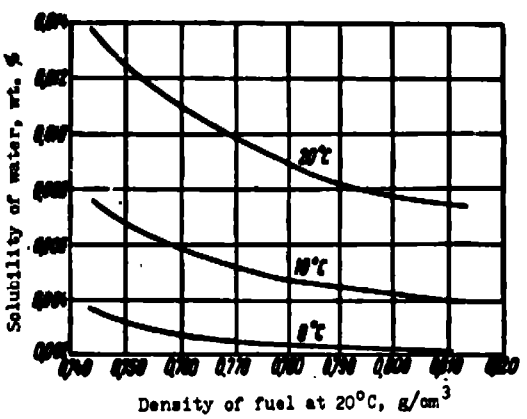


Fig. 23. Influence of density of jet propellant on solubility of water at various temperatures.

Influence of Humidity of Air on Water Accumulation of Fuels

Solubility of water in fuel is proportional to partial pressure of water vapor above surface of fuel, i.e., atmospheric humidity. Therefore at the same temperature the content of dissolved water in fuel will be the greater, the higher the humidity of external air.

With very high atmospheric humidity (rain, fog) sometimes such a strong water accumulation of fuel is observed that it becomes slightly turbid owing to incomplete dissolution of water. It is impossible to fill aircraft with such a fuel, and if wet, becoming turbid fuel is observed in aircraft tanks, it is necessary to pour it off immediately.

Solubility of Fuels in Water

It is considered that aviation fuels are not mixed with water and are not dissolved in it. However in reality aviation fuels do dissolve in water, although in very small amount. Let us give data about the solubility of fuel in water at 10°C (in g/kg of water):

Aviation gasoline	17
Auto gasoline	11
Aviation kerosene	9
Benzene	175

With increase of temperature the solubility of fuels in water increases somewhat.

17. FORMATION OF CRYSTALS OF ICE IN JET FUELS, ICING AND CLOGGING OF AIRCRAFT FILTERS

According to the American press [50], around 11% of all accidents in military jet aviation of the United States occur due to icing of filters and disturbance of normal work of fuel system of aircraft. Until recently all these phenomena were explained by clogging of aircraft filters with ice crystals, which are formed in jet fuels during their cooling and accumulation on the surface of filtering elements, preventing normal passage of the fuel through filter and thereby disturbing normal work of the engine.

However many years of experience of operation of jet aircraft in civil aviation showed that the conventional explanation of the mechanism of clogging of aircraft filters with ice crystals is erroneous. This is confirmed by the following facts.

1. Accumulation of crystals of ice on filters of fine purification of aircraft is never observed, although the thickness of filters of metallic grid is around 20 μ, and of paper — around 15 μ; consequently, these filters are able to hold back part of the crystals of ice whose diameter oscillates within limits of 10-40 μ [57].

2. In most cases crystals of ice clog aircraft filters of coarse purification with pores around 100 μ in diameter, although such filters are incapable of delaying crystals of ice formed in the fuel.

3. Frequently crystals of ice clog safety grids of pumping pumps with diameters of apertures more than 2 mm, and consequently, they absolutely cannot hold back crystals of ice formed in the fuel.

4. In winter period during work of aircraft on "cold-treated fuel," without use of ethyl Cellosolve, in fuel there is always a large amount of ice crystals. In practice there was not one case of clogging of aircraft filters with ice crystals during work on cold-treated fuel.

5. Numerous inspections of filters of coarse purification, safety grids of pumping pumps and other aggregates of fuel system of jet aircraft showed that clogging of them is caused by icing, and not by precipitation of ice crystals.

What are the causes of icing and clogging of aircraft filters?

On the basis of conducted research and analysis of available materials it becomes evident that clogging of aircraft filters is caused not by accumulation on filters of ice crystals, but by icing of filters, which occurs as a result of crystallization of supercooled drops of water during their collision with hard cold surface of the filter or other aggregates of fuel system of aircraft [51].

Process of icing (clogging) of aircraft filters proceeds analogously to well-known phenomenon of icing of aircraft in flight, when supercooled drops of water in the clouds, during collision with cold surface of wing edge are instantly crystallized.

Mechanism of icing of aircraft filters can be presented in the following manner. During cooling of jet propellant in tanks of aircraft, water dissolved in it starts gradually to separate in the form of smallest drops (10-40 μ), forming an aqueous microemulsion. Drops of water finely dispersed in the fuel and also drops of water

separated from the solution, almost never freeze immediately, i.e., they are not turned into crystals of ice, but can for a long time be in the fuel in liquid supercooled state.

Microdrops of water in suspension in medium of cold fuel are rapidly cooled, taking temperature of fuel, remaining with this in liquid form.

Rate of cooling of microdrops of water in suspension in medium of cold fuel are rapidly cooled, taking temperature of fuel, remaining with this in liquid form.

Rate of cooling of microdrops of water in medium of motionless air is listed in Table 59.

Numerous investigations of phenomenon of supercooling of drops of water allowed us to establish the following general rules.

Table 59. Rate of Cooling of Microdrops of Water in Medium of Motionless Air

Diameter of drops of water, μ	Rate of cooling, sec, at a temperature, °C		
	from 0 to −8°C	from 0 to −16°C	from 0 to −18°C
10	14	28	42
100	14	28	42
500	70	139	200

1. The less the diameter of drops of water, the lower the temperature to which their supercooling is possible.

Thus, microdrops of water with a dimension less than 100 μ could be in liquid phase during cooling of them to temperature of -30 to -41°C [52] (Table 60).

Table 60. Temperature of Supercooling of Drops of Water Depending on Their Diameter

Diameter of drops of water, μ	10	50	100	300	600	1000	3000	6000
Temperature of supercooling, °C	−40	−36	−30	−28	−24	−22	−19	−16

2. The faster drops of water are cooled, the lower the temperature to which their supercooling is possible.

Thus, in fuel cooled to a temperature of -10 to -40°C, there can be microdrops of water in liquid state in large amount.

When the flow of fuel containing in itself supercooled drops of water passes through fuel lead and encounters on its path an obstacle in the form of safety grid of pumping pumps or filters of coarse purification, supercooled drops of water collide with hard cold surface of filter. As a result of this collision they are instantly turned into ice, causing icing of grid of filters or other parts of fuel system of aircraft.

This explains icing and clogging with crystals of ice of filters of coarse purification with dimensions of pores around 100 μ, which practically are incapable of holding back crystals of ice with a dimension less than 40 μ which are formed in the fuel.

Possible Methods of Destruction of Supercooled Drops of Water in Fuels

By preventing formation in fuel of supercooled drops of water it is possible to remove the danger of icing of aircraft filters. There exist several methods of destruction of supercooled drops of water contained in jet propellants.

1. Strong cooling of fuel in ground reservoirs with subsequent intense pumping and filtration of it, when collision of supercooled drops of water with cold surface of filter is achieved, in many cases may cause crystallization of supercooled drops of water.

2. Crystallization of supercooled drops of water can be significantly accelerated, if into the fuel there are introduced centers of crystallization; snow, hoarfrost or icicles [51]. However this is

unacceptable for operation. Mechanical impurities usually contained in fuels as a rule are not centers of crystallization.

Centers of crystallization can cause crystallization of supercooled drops of water in fuel only in the case when collision occurs, for instance, of a snowflake with drop of water, or when the distance between snowflake and drop of supercooled water is not more than 58 μ.

3. With addition to jet propellant of ethyl Cellosolve the possibility of formation of supercooled drops of water is prevented, and thus the danger of icing of aircraft filters can be removed. Mechanism of action of ethyl Cellosolve in this case consists of the fact that being mixed with microdrops of water occurring in the fuel, it will form antifreeze, having low freezing point and able to be in the fuel in dissolved form (Fig. 24).

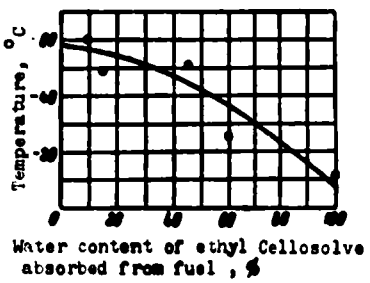


Fig. 24. Influence of water content of ethyl Cellosolve on temperature of fuel at which icing and clogging of aircraft filters occurs.

Preheating of fuel in flow, as this is carried out on aircraft Boeing-707, DC-8, Caravele, Viscount, and others, prevents the possibility of supercooling drops of water dispersed in the fuel; thereby the danger of icing of aircraft filters is removed.

18. ELIMINATION OF CRYSTAL FORMATION IN JET FUELS

In the foreign press descriptions are frequently given of aviation catastrophes and flight accidents caused by the formation of ice crystals in jet propellants. Thus it was reported [63] that of 352 investigated flight accidents in the last 30 months 37 cases were caused by clogging (icing) of filters with ice crystals.

Starting from the 1950's, in the United States intense works have been conducted on the study of processes of crystal formation in jet propellants and on the development of methods of elimination of the danger of stopping up of filters in fuel system of aircraft with ice crystals.

For military jet aircraft of the United States an automatic system was developed of supply of alcohol to filters in those cases when they start to clog with ice crystals and to ice. However this method of combatting the danger of crystal formation was not justified, since it permitted to remove clogging of filters, but did not eliminate formation of ice crystals in the fuel and their deposit in other places of fuel system of aircraft before the filter.

Later for heavy military aircraft and for civil transport aircraft on the United States and England there was developed a system of preheating the fuel proceeding to the engine with air removed from

the compressor, or with oil. With this the fuel is heated to a temperature higher than 0°C, and thereby the danger of stopping up of filters and pipelines with ice crystals in the zone after the preheater is eliminated.

This system is used also now for certain types of foreign transport jet aircraft.

In recent years in the United States intense works have been conducted on search for chemical substances whose addition can eliminate the formation of ice crystals in the fuel. Thus, by the order of the United States Air Force research organizations checked more than 150 samples of chemical compounds for the purpose of finding additions for elimination of crystal formation in jet propellants [64]. At present such an addition has been found, and in August, 1960, it passed operational tests in strategic aviation of the United States on 15 B-52E aircraft and on 10 KC-135 aircraft.

It was published [65] that the discovered addition PFA-55 MB, added to jet propellants for prevention of crystal formation, consists of 90% ethyl Cellosolve and 10% glycerine. Effectiveness of this addition is shown in Table 61.

Prevention and elimination of formation of crystals of ice in jet propellants at present is achieved by introduction of addition dissolved in fuel and possessing irreversible hygroscopicity.

Inasmuch as one of the indispensable properties of such additions is their solubility in fuel and water, additions can be washed, if during storage and transport the fuel touches water. This characteristic of fuels with an addition is their deficiency, and creates a number of difficulties in operation. But it can be removed by introduction into fuel of addition directly at places of its consumption.

Table 61. Effectiveness of American Addition for Elimination of Clogging (Icing) of Filters with Ice Crystals [33]

Jet propellant	Total content of dissolved water and water of emulsion in fuel, %	Introduction of addition to fuel, % by volume	Temperature of fuel at which filter clogs, °C
Fuel JP-4	0,01	0	—11,1
The same	0,08	0	—2,2
"	0,01	0,1	—60
"	0,08	0,1	—60
Fuel JP-5	0,08	0	—8,3
The same	0,01	0,05	—19
"	0,08	0,05	—25
"	0,08	0,1	—51,1

Ethyl Cellosolve introduced into fuel, being evenly distributed through the entire mass of jet propellant, is mixed with hygroscopic moisture, forming antifreeze; thereby is eliminated the separation of water and formation of ice crystals.

Destruction of Ice Crystals in Jet Fuels

Inasmuch as ice crystals formed in jet propellants in large quantities represent a danger for operation of aircraft, it is necessary to remove or to destroy (dissolve) them.

Big crystals of ice can be partially removed from fuel by filtration through microfilter. However to remove ice crystals from fuel most completely is possible by dissolution of them or by melting, adding special addition to fuel. Addition for destruction (melting) of ice crystals can be such a liquid which is dissolved well in the fuel. In most cases as additions are used substances which are used for prevention of crystal formation in fuels (alcohols, esters). For destruction of ice crystals in fuel it is usually sufficient to add to it less than 0.3% of addition.

With large content of ice crystals in fuel their fusing sometimes is accompanied by light turbidity of fuel, gradually disappearing. Turbidity appears, obviously, due to strong water accumulation of separate parts of component owing to dissolution in them of ice crystals.

Sometimes due to strong water accumulation, from fuel a deposit precipates, which represents a mixture consisting of 60-65% of addition and 35-40% of fuel.

On interface of precipitate and fuel in some cases tarry substances, different impurities and other contaminations contained in the fuel concentrate.

Cold-treating of Jet Fuels with Water Content in Conditions of Operation

To prevent the danger of entry of ice crystals into fuel system of aircraft it is expedient that process of cold-treating of fuels occurred not in aircraft tanks, but in stationary cisterns. With this goal fuels kept in underground cisterns for two-three days up to their delivery for servicing of machines are pumped into ground reservoirs, where they are cooled and excess moisture freezes out.

With this the lower the temperature to which fuel is cooled, the greater the part of hygroscopic water will be separated from the fuel.

19. PYROTECHNICAL CHARACTERISTICS OF JET FUELS

Petroleum fuels used in aviation are combustible and easily inflammable liquids, vapors of these fuels with air form explosive mixtures. In conditions of operation of aircraft sources of fire can be:

1) flash (ignition) of fuel vapors from open flame of heated wire or from electrical spark;

2) spontaneous inflammation of fuel during its falling on heated surface, if the temperature of this surface is higher than temperature of spontaneous inflammation of fuels;

3) explosion of fuel vapors in gas space of tanks or in another closed space during appearance of charge of static electricity or during hit of igniting shell.

For estimate of potential fire danger of jet fuels the following basic characteristics are taken.

1. Temperature limits of formation of explosive mixtures of fuel vapors with air.

2. Concentration limits of explosive mixtures.

3. Temperature of spontaneous inflammation during contact of fuel with strongly heated surface.

4. Flash point of fuel.

Burning and Flame Propagation

One of the most important characteristics of burning of fuel-air mixtures is the speed of flame propagation. Precisely this characteristic to a significant degree determines the inflammability of fuels.

At the flash point and above over an open surface of liquid fuel a fuel mixture will be formed. If it is ignited from an outside source, then flame will spread along the surface of liquid fuel at a rate of the order of 1.2-1.4 m/sec.

In fuel-air mixture, in a motionless state in closed volume or during its laminar movement, flame spreads with speed of 0.3-0.6 m/sec. In conditions of turbulent movement of mixture, depending on pressure, intensity, turbulence and composition of mixture, flame spreads with speed of 10-30 m/sec.

Flash Point of Fuels

Recently it was established that the flash point of fuels, determined in closed vessel, is that temperature at which pressure of vapors of given type of fuel reaches 7-10 mm Hg. Thus, if flash point of fuel T-1 is equal to 30°C, this means that at 30°C the pressure of vapors of fuel T-1 reaches approximately 7-10 mm Hg.

Flash point is that temperature at which above the surface of the fuel there will be formed an explosive concentration of fuel vapors in air.

As was already indicated above, the flash point depends on pressure of fuel vapors (Table 62).

Table 62. Influence of Vapor Pressure of Jet Propellants on Flash Point

Fuel	Vapor pressure at 38°C, mm Hg	Flash (GOST 1421-53), °C
Soviet Union		
Fuel T-1	25	30
" TS-1	35	28
T-2	75	+4
T-2	100	-14
Aviation gasoline B-70	200	-28
" " B-95/130	320	-38
England		
Aviation Kerosene JP-5	10	60
" " ATK	15	34
Fuel JP-4	100	-14
" JP-4	160	-23

Classification of Inflammability of Fuels According to Flash Point

In Soviet Union and abroad frequently the inflammability of petroleum fuels is classified by flash point, determined in closed crucible. This classification gives the most approximate idea about the real inflammability of different types of petroleum fuels. However this method of classification of fuels is widely used and officially accepted in national economy of Soviet Union (Table 63).

In accordance with classification given in Table 63, fuel of wide fractional composition of type T-2 and aviation gasolines will belong to Class I of inflammability.

Table 63. Classification of Inflammability of Petroleum Fuels, Accepted in Ministry of Naval Fleet and Ministry of River Fleet of Soviet Union [34]

Class (category) of inflammability of fuels	Flash point of fuels, °C	
	according to manual No. 5, 1948, Ministry of Naval Fleet	according to order No. 108, April 27, 1951, Ministry of River Fleet
I	Lower than 28	Lower than 28
II	From 28 to 65	From 28 to 45
III	From 65 and above	From 45 to 120

Fuels T-1 and TS-1, having flash point of 28°C and above, will belong to Class II of inflammability.

Temperature Limits of Formation of Explosive Mixtures of Fuel Vapors

Formation of explosive mixtures of fuel vapors with air is possible only in definite temperature limits. In this connection it is accepted to consider lower and upper temperature limits of formation of explosive mixtures.

As the lower temperature limit of explosive mixtures is taken that minimum temperature of fuel at which the pressure of fuel vapors reaches such a magnitude when in closed space of tank an explosive mixture will be formed. With further cooling of fuel the mixture is impoverished so much that it becomes inflammable with difficulty.

Table 64. Temperature Limits of Explosiveness of Mixtures of Fuel with Air at Ground Level

Fuel	Lower limit, °C	Upper limit, °C	Fuel	Lower limit, °C	Upper limit, °C
Aviation gasoline B-70.....	-34	-4	Fuel T-2.....	-18	14
" " B-91/115.	-38	-5	" TS-1.....	28	57
" " B-95/130.	-37	-5	" T-1.....	27	59
" " B-100/130	-34	-4	" T-5.....	60	87

As the upper temperature limit of explosive mixtures is taken that maximum temperature of fuel at which a mixture of fuel vapors with air still retains explosive properties. With further increase of temperature the mixture is strongly overenriched with fuel vapors and becomes incombustible.

Temperature limits of explosiveness of mixtures of different types of fuels with air are given in Table 64.

Temperature Zones of Formation of Explosive Mixtures By Altitude

For different types of fuels, possessing different pressure of saturated vapors and consequently also different volatility,

sufficiently definite ranges of temperatures were established, within whose limits can be formed explosive mixture at different altitude.

With rise in altitude, when external atmospheric pressure drops, evaporation of fuel is increased. Due to this explosive mixtures of fuel vapors with air at an altitude can be formed at significantly lower temperatures than on the ground at standard atmospheric pressure. Therefore the temperature zone of explosive mixtures with respect to altitude shifts in the direction of lower temperatures.

It was established [35] that for every type of fuel depending on the pressure of its vapors and volatility there is a definite altitude (characterized by degree of rarefaction), above which strongly overenriched explosive mixtures begin to be formed (Table 65).

Temperature zones of formation of explosive mixtures of different types of fuels are presented in the form of three graphs, where on the axis of abscissas are plotted temperatures of fuel, and on the axis of ordinates — altitude in m (residual pressure in mm Hg). Two lines on these graphs delimit the zone of explosive mixtures. Right line limits the area of overenriched mixtures, and left line — area of lean mixtures.

From the graphs it is clear that explosive zone for mixtures of fuel T-1 on the ground is within limits of 25-65°C; at altitude of 15,000 m the explosive zone is somewhat narrowed and shifts in the direction of lower temperatures (5-40°C). At an altitude exceeding 15,000 m, explosiveness of mixtures becomes unstable due to their overenrichment owing to strong evaporation of fuel T-1 (Fig. 25).

Explosive zone for fuel TS-1 is within limits of 15-60°C; at an altitude of 15,000 m the explosive zone is somewhat narrowed and shifts

in the direction of lower temperatures: from 0 to 30°C (Fig. 26). At an altitude exceeding 15,000 m, explosiveness of mixtures becomes unstable due to their overenrichment owing to strong evaporation of fuel TS-1.

Explosive zone on land for fuel T-2 is from -10°C to 40°C; at an altitude of 14,000 m it is somewhat narrowed and shifts in the direction of lower temperatures: from -22 to 15°C (Fig. 27). At an altitude exceeding 14,000 m, explosiveness of mixtures becomes unstable due to their overenrichment owing to strong evaporation of fuel T-2.

Table 65. Temperature Limits of Explosiveness of Mixtures of Fuel with Air at an Altitude of 15,000 m

Fuel	Pressure of fuel vapors at ground level at 38°C, mm Hg	Lower limit, °C	Upper limit, °C
T-1	25	5	40
TS-1	35	0	30
T-2	100	-22	5
B-70	200	-30	15

Explosive zone for aviation gasoline B-70 is from -25 to 20°C; at an altitude of 11,000 m explosiveness of mixtures becomes unstable due to their overenrichment owing to strong evaporation of gasoline B-70.

All these discussions concern the formation of explosive mixtures in fuel tanks of aircraft picture is observed in emptied fuel tanks, in which actually there will be always a certain amount of residual fuel. Space of these tanks can be filled with explosive mixture (analogous to empty gasoline barrels, which are explosive).

To what altitude the explosiveness of mixtures in "empty" fuel tanks of aircraft is kept, it is difficult to give an exact answer. This depends not only on the physicochemical propellant properties, but also on the amount of residual fuel in "empty" tanks of aircraft, which it is not always possible to determine exactly. Therefore for guarantee of safety one should consider that in "empty" tanks of aircraft during flight at all operational altitudes there can be explosive mixtures.

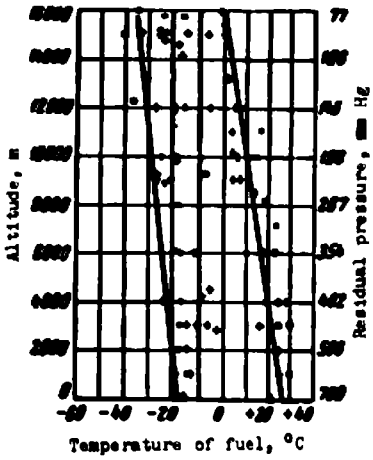


Fig. 25. Temperature limits of formation of explosive mixtures of fuel T-1 depending on altitude (pressure of fuel vapors 45 mm at 38°C).

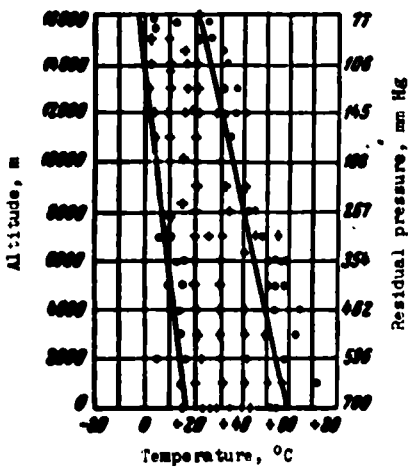


Fig. 26. Temperature limits of formation of explosive mixtures of fuel TS-1 depending on altitude (pressure of fuel vapors 50 mm Hg at 38°C).

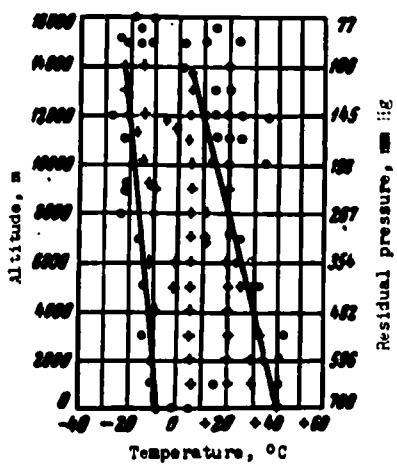


Fig. 27. Temperature limits of formation of explosive mixtures of fuel T-2 depending on altitude (pressure of fuel vapors 100 mm Hg at 38°C).

Foam Formation in Tanks and Explosiveness of Foam

Fuel poured into tanks of aircraft always is saturated with dissolved air; the lower the surface tension of fuel, the more air can be dissolved in it.

During climb of aircraft, when external atmospheric pressure drops, air dissolved in fuel gradually starts to be separated. With mechanical mixing of fuel separation of air from fuel is significantly accelerated. Thus, inclusion of booster pump during flight at a great altitude sometimes causes so much violent separation of dissolved air from fuel that on the surface of fuel in tanks of aircraft a great layer of foam will be formed. Foam formed from bubbles of air which was distributed in fuel possesses great explosiveness and combustibility even at relatively low temperatures. In such foam, as in vapor-air mixture, flame spreads with great speed. Special explosiveness of foam is caused by increased concentration of oxygen in air separated from fuel. This is explained by the fact that solubility of oxygen in fuel at 20°C is approximately 1.6 times higher than solubility of nitrogen.

Concentration Limits of Inflammation of Explosive Mixtures of Vapors of Jet Fuels

Concentration limits of inflammation are called limiting concentrations of fuel vapors in air, with which inflammation of mixture and propagation of flame are possible.

In Table 66 are listed experimental data of concentration limits of inflammation of explosive mixtures of different kinds of aviation gasoline and jet propellants.

Table 66. Concentration Limits of Inflammation of Explosive Mixtures of Fuel Vapors in Air (in % by Volume)[34]

Fuel	Density, g/cm³	Lower limit	Upper limit
Aviation gasoline B-70.....	0.745	0.79	5.16
" " B-91/115...	0.729	0.89	5.46
" " B-95/130...	0.736	0.98	5.48
" " B-100/130..	0.728	0.98	5.48
Fuel T-2.....	0.765	1.1	6.8
" TS-1.....	0.779	1.2	7.1
" T-1.....	0.813	1.4	7.5

Dependence of Flash Point on Pressure of Fuel Vapors

Flash point of fuel actually shows minimum temperature of fuel at which formation of explosive mixtures is possible, and lower limit of explosiveness of mixtures — minimum concentration of fuel vapors in air at which burning of the mixture is possible.

Using the indicated dependence, it is possible by the flash point of fuel to find the lower limit of explosiveness of mixtures or by limit of explosiveness of mixtures to calculate the flash point.

Knowing the lower concentration limit of explosiveness of mixtures, it is possible to calculate the pressure of fuel vapors at the flash point:

$$p_{fl} = \frac{v \cdot p}{100},$$

[fl = fl = flash]

where p_{fl} is the pressure of fuel vapors at the flash point in mm Hg;

v is the lower concentration limit of explosiveness of mixtures in % by volume;

p is the pressure of mixture of fuel vapors with air in mm Hg.

Determination of Content of Fuel Vapors in Air

If temperature of fuel and pressure of its saturated vapors at a given temperature are known, then the concentration of fuel vapors

in air can be calculated by the formula:

$$V = \frac{p_T \cdot 100}{p_B},$$

[T = f = fuel, B = a = air]

where V is the concentration of fuel vapors in air in % by volume;

p_f is the pressure of saturated vapors in mm Hg;

$p_{f\ a}$ is the pressure of mixture of fuel vapors with air (in most cases it equals atmospheric) in mm Hg.

Volume concentration of fuel vapors in air can be scaled in weight according to the formula:

$$V = \frac{V \cdot m}{2,24}.$$

Temperature of Spontaneous Inflammation of Fuels

Spontaneous inflammation is an important characteristic of inflammability of fuels. In operational conditions spontaneous inflammation is possible when liquid fuel or its vapors strikes a strongly heated surface. From experience of operation it is known that such cases are possible in particular during disturbance of airtightness of fuel leads mounted on body of motor, and when stream of fuel strikes a strongly heated part of motor. For guarantee of fire safety it is important to know what temperature of metallic surface can ignite fuel striking it (Table 67).

Temperature of spontaneous inflammation of fuel is not a constant magnitude; it depends on the method of appraisal used.

Significant influence on temperature of spontaneous inflammation is the chemical composition of fuel. In most cases, the higher the molecular propellant weight and the heavier its fractional composition, the lower the temperature of spontaneous inflammation. Ethylated gasolines as a rule have a higher temperature of spontaneous inflammation than unethylated, which is caused by the presence in gasolines

of TES.

From the data of Table 67 it is clear that with loading of fractional composition the temperature of spontaneous inflammation of fuels drops somewhat; when fuel strikes a heated surface whose temperature is 325-430°C, fuel can inflame and fire will appear.

Table 67. Temperature of Spontaneous Inflammation of Aviation Fuels

Fuel	Flash point, °C	Temperature of spontaneous inflammation of fuel, °C	Temperature of heated plate, causing spontaneous inflammation of fuel, °C
T-1	30	220	325
TS-1	28	218	325
T-2	-14	233	330
B-70	-30	331	430

Temperatures spontaneous inflammation (in °C) of different types of native [Soviet] fuels practically are close to those which were obtained in the United States by the drop method.

ATK 228
JP-3 228
JP-4 242
B-73 258
B-100/130 + TES 440

Influence of Altitude on Temperature of Spontaneous Inflammation of Aviation Fuels

In the literature [36] there are the following data about the altitude effect (lowering of pressure) on temperature of spontaneous inflammation of aviation fuels (Table 68).

Table 68. Altitude Effect on Temperature of Spontaneous Inflammation of Fuels

Fuel	Delay of inflammation at 742 mm Hg, sec	Temperature of spontaneous inflammation in °C at pressure	
		742 mm Hg (on ground)	370 mm Hg (altitude 5700 m)
Aviation gasoline 100/130	3	440	553
Fuel ATK.....	120	228	462
" JP-3.....	187	238	449
" JP-4.....	185	242	444

Spontaneous Combustion of Combustible Liquids

There exist a number of combustible liquids able to be oxidized intensely in air at the usual temperatures (16-20°C). Under certain conditions, when the amount of heat liberated in the process of oxidation exceeds heat transfer in external medium, spontaneous combustion of oxidizing liquid can occur. Such liquids are called self-igniting. Liquids inclined to spontaneous combustion can be conditionally divided into two groups.

First group – liquids possessing the capacity for spontaneous combustion during contact with air, for instance, vegetable oils, turpentine and some animal fats on developed surfaces of fibrous materials (wadding, cotton, cotton waste, etc.).

Second group – liquids capable of spontaneous combustion only during contact or chemical influence with other substances. For instance, during contact of ethylene glycol and glycerine with potassium permanganate, and also alcohols with peroxides, etc.

In practice the capacity of vegetable oils for spontaneous combustion is determined by iodine number. It is considered that liquid with iodine number higher than 100 is dangerous in fire relationship for inclination to spontaneous combustion.

Speed of Burnout of Fuels from Surface

As speed of burnout of fuels from the surface is taken the per weight amount of fuel burning from unit of surface in unit of time, for instance $kg/m^2 \cdot hr$. In some cases the speed of burnout is expressed by so-called linear burning rate, which represents the height of layer of fuel (mm), burning in unit of time (min) (Fig. 28).

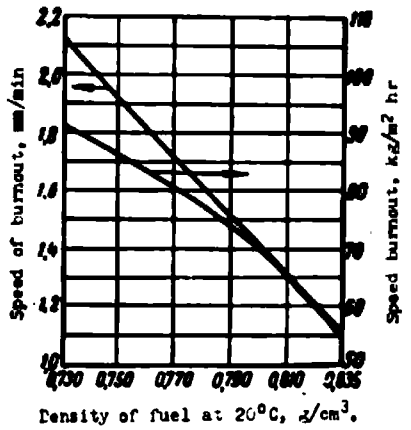


Fig. 28. Speed of burnout of fuel from surface depending on its density.

Table 69. Speed of Burnout of Fuel from Surface in Reservoirs [37]

Fuel	Density of fuel, g/cm^3	Speed of burnout of surface in reservoirs of small diameter		Heat-release rate of surface of evaporation of fuel, $kcal/m^2 \cdot hr$
		mm/min	$kg/m^2 \cdot hr$	
Aviation gasoline	0.730	2.10	91.98	12,390
Auto gasoline	0.770	1.75	80.85	12,300
Kerosene	0.835	1.10	55.11	10,710

Depending on density and fractional composition, the speed of burnout from surface will be different. The lower the density of fuel, the greater the speed of its burnout (Table 69).

Prevention of Explosion of Fuel Vapors in Aircraft Tanks

On certain types of military jet aircraft abroad inert gas is introduced for the purpose of prevention of explosion of fuel vapors into the gas space of fuel tanks.

In Table 70 are listed some data about amount of inert gas which it is necessary to introduce into mixture of fuel vapors in order to make them nonexplosive.

Table 70. Fire-extinguishing Concentrations of Gases for Elimination of Explosion of Vapors of Gasoline and Kerosene (Concentration in % of air)

Gas	Necessary amount of gas, % by volume.	
	According to Demidov [37]	According to Yursenev [29]
Carbonate	23.0	21.2
Nitrogen.....	31.0	30.8
Methyl bromide..	4.0	—
Carbon tetrachloride	7.5	8.0

From the data of the table it is clear that the fire-extinguishing effect of halide derivatives is a few times higher than carbon dioxide or nitrogen. Different fire-extinguishing effectiveness of gases P. G. Demidov explains by different mechanism of their action on process of burning. In the opinion of P. G. Demidov, during introduction into zone of burning of fuel-air mixtures, for instance methyl bromide or carbon tetrachloride (exothermic reaction), burning is disturbed and liberation of heat sharply drops, as a result of which burning is ceased.

The fire-extinguishing effect of carbon dioxide and nitrogen consists in the fact that the concentration of oxygen in the mixture becomes lower than that minimum at which burning is possible. According to the author, during introduction into hot mixture of carbon dioxide, burning is ceased when content of oxygen is below 14-18% and introduction of methyl bromide — when content of oxygen drops to 20.6%.

The use of inert gas for filling of free space of fuel tanks is connected with necessity of installation of aircraft of additional

equipment. Total weight of gas and equipment on the average amounts to 1 kg for each 100 liters of capacity of fuel tanks. This means that for aircraft, the capacity of whose fuel tanks amounts to 30,000 liters, the weight of gas and equipment will amount to around 300 g.

Influence of Pressure on Temperature of Spontaneous Inflammation of Jet Fuels

Experiments established that the higher the pressure, the lower the temperature of spontaneous inflammation of jet propellants (Table 71).

Table 71. Influence of Pressure on Temperature of Spontaneous Inflammation of Propellants [8]

Pressure, atm (tech.)	Temperature of spontaneous inflammation, °C	
	Fuel JP-4	Fuel JP-5
1	251	247
5	191	213
9	190	209

20. ELECTRICAL PROPERTIES OF JET FUELS

In section electrical properties of jet propellants is considered: the electrical conductivity, electrical excitability and dielectric constant of fuels. These characteristics of jet propellants have important operational value.

Specific Electrical Conductivity

Specific electrical conductivity of fuels is called the quantity of electricity which flows in 1 sec through 1 cm^2 of cross section of fuel with gradient of electrical field of 1 v per 1 cm and is expressed in $ohm^{-1} \cdot cm^{-1}$.

Independently of grade and chemical composition, dry, pure hydrocarbon (petroleum) fuels with no water content have specific resistance from 1×10^{-15} to 1×10^{-12} $ohm^{-1} \cdot cm^{-1}$.

Entry into propellant of even insignificant quantities of contaminations leads to sharp increase of electrical conductivity of fuels, which is clear from the following data (in $ohm^{-1} \cdot cm^{-1}$).

Fuel JP-5 pure, dry	1×10^{-14}
The same, moistened	1×10^{-13}
The same +0.0005% asphalt, not soluble in gasoline	1.2×10^{-12}

Dielectric Constant

Dielectric constant is the name for a value, which shows how

many times the force of interaction between two electrical charges, at definite distance from each other in given medium (dielectric) is weakened as compared to the force of interaction between these charges, but in vacuum space.

Dielectric constant of jet propellants characterized their insulating properties and depends on temperature, frequency of current and properties of fuels. On dielectric constant of jet propellants in aviation is based the action of equipment for measurement of quantity and consumption of fuels in aircraft during flights.

In Fig. 29 is listed dependence of dielectric constant of jet propellants of the United States on temperature with frequency of current of 400 cps.

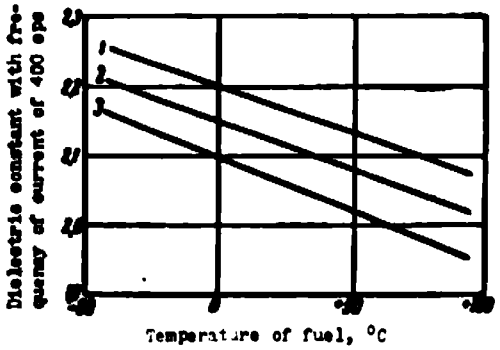


Fig. 29. Dielectric constant of typical grades of jet propellant of the United States (NACATN 3276) 1 — avcat (JF-5); 2 — avtour (ATK); 3 — avtag (JP-4).

In contemporary aviation the reserve of fuel in tanks of aircraft is measured by full gauge. This method is based on change of electrocapacitance of transducer-capacitor due to change of quantity of fuel in aircraft tanks. Transducers, established in fuel tanks of aircraft in vertical positions, consist of several, tubes in cantilever arrangement with air gaps between them. During filling of tanks with fuel also gap between tubes is filled. Due to the fact that the dielectric constant of fuel differs from the dielectric constant of air, with change of level of fuel in tanks and, consequently, in gaps between tubes, the electrical capacitance of transducer is changed.

Dielectric constant of air is a constant magnitude and is equal to 1.0006, whereas the dielectric constant of jet propellants is a

variable magnitude and depends on the grade (density) of fuel and on the temperature.

With increase of temperature the dielectric constant of fuel drops; with increase of density of fuels the dielectric constant is increased [38] (see Fig. 29). In connection with this quantity of fuel in tanks of aircraft with the help of electro-capacitive fuel gauge is measured taking into account the density and temperature of measured fuel.

With the use of a graph where the dielectric constant of three grades of propellants used in England and the United States is shown, one should consider that density at 20°C of fuel JP-5 amounts to around 0.830, of fuel ATK around 0.795 and of fuel JP-4 around 0.755 g/cm^3 which approximately corresponds to density of native [Soviet] grades of jet propellants T-5, T-1, TS-1 and T-2.

Electrical Excitability

Electrical excitability of jet propellants conditionally called the phenomenon of appearance of charge of static electricity during work with fuels.

During pumping, filling and overflow, but also during fueling of aircraft with gasoline and jet propellants, there are often cases of explosions and fires, whose cause is incomprehensible. As research showed, significant part of such explosions and fires during work with oil products is caused by charge of static electricity.

Struggle with static electricity and development of preventive measures significantly are facilitated by the fact that now there is clear idea about the mechanism of formation of charges of static electricity during work with oil products. In particular, it was established that with certain conditions even in fuel in a motionless

state, formation of static electricity is possible, this charge can cause explosion and fire if the necessary preventive measures are not taken. Below are set forth causes of formation of charge of static electricity in fuels [39].

Formation of static electricity during movement of fuel. Static electricity appears in the following cases:

1) during friction of liquid fuel against hard surface of pipeline, walls of reservoir and filter;

2) during friction of particles of fuel among themselves, during passage of fuel through other liquids, for instance, water and so forth;

3) during passage of drops of finely atomized fuel through air or steam mixture (atomization of fuel).

Formation of static electricity in fuel in a motionless state. Static electricity can appear;

1) during precipitation from fuel of solid suspended particles,

2) during precipitation from fuel of liquid suspended particles, for instance, drops of water or other chemical substances, and also during passage through layer of liquid fuel of bubbles of air, vapors of light hydrocarbons, etc.,

3) during passage through steam space of drops of water (rain), snowflakes, etc.

American Petroleum Institute studied 63 cases of explosions of fuel cisterns, accompanied by fire, and determined the following causes of formation of charge of static electricity.

Causes of formation of charge of static electricity	Fires	
	Number	%
Mixing and pumping of fuels	37	58
Incorrect decantation and filling of containers with fuel (atomization of fuel).	10	16
Admission of damp steam into fuel	6	10
Overflow and pumping of fuel at a great rate.	4	6
Switching off electricity on body of cistern.	4	6
Atomization of liquid fuel in air	1	2
Blow of lightning (work during thunderstorm).	1	2
Total	63	100

Influence of electrical conductivity on electrical excitability of jet propellants. Experiments established that ability of fuel to form static electricity during pumping depends on its specific electrial conductivity.

Speed of formation of static electricity during pumping of fuel depending on its specific electrical conductivity is characterized by the following data;

Specific electrical conductivity of fuel, $ohm^{-1} \cdot cm^{-1}$	Quantity of charges of static electricity after 10 min of pumping with voltage on discharger of 7 kv
1×10^{-15}	1
5×10^{-15}	35
1×10^{-14}	110
5×10^{-13}	500
1×10^{-13}	600
5×10^{-12}	550
1×10^{-12}	250
5×10^{-11}	2
$1 \times 10^{-}$	0

Rate of dispersion (drop) of charge of static electricity is also in direct dependence on specific electrical conductivity of fuel; the lower the electrical conductivity, the slower formed charge of static electricity is dispersed,

Specific electrical conductivity of fuel, $ohm^{-1} \cdot cm^{-1}$	Rate of dispersion of charge of static electricity by 50%, sec.
10^{-15}	
10^{-14}	130
10^{-13}	13,0
10^{-12}	1,30
10^{-11}	0,13
10^{-10}	0,013

Different grades of jet aviation and motor fuels possess different ability to form static electricity. Below are described data about quantity of charges of static electricity (voltage on discharger 7 kv) for 10 minute pumping;

Isooctane, n-heptane, cetane	0-12
Toluene and xylene	14-50
Aviation gasolines and auto gasolines	41-59
Jet propellant JP-4	1-71
Unpurified kerosene	7-82
Jet propellant JP-5	10-140
Diesel fuel	5-420

On speed of formation of static electricity very many operational factors have influence, for instance, speed of pumping, presence in fuel of mechanical impurities, water, air and temperature.

Influence of speed of pumping of fuel. All other conditions being equal, the higher the speed of pumping or overflow of fuel, the more static electricity will be formed (Table 72).

Influence of purity of jet propellant. Presence in fuel of mechanical impurities renders significant influence on speed of formation of static electricity; the purer the fuel, the less the charges of static electricity (voltage on discharger 7 kv),

JP-5 without mechanical impurities	15
JP-5 + finely crushed deposits from cistern.	27

Consequently, with removal of mechanical impurities (filtration) the possibility of formation of static electricity during pumping or

Table 72. Influence of Speed of Pumping of Fuel on Formation of Static Electricity [39]

Fuel	Number of charges of static electricity after 10 min of pumping (voltage 7 kv)	
	Speed of pumping 500 ml./min	Speed of pumping 1500 ml./min
JP-4	24	138
JP-5	16	84
JP-5	8	28
JP-4	3	14

fueling of aircraft decreases (Table 73).

Table 73. Influence of Purification of Jet Propellant on Formation of Static Electricity During Pumping

Method of purification	Specific electrical conductivity, $ohm^{-1} \cdot cm^{-1}$	Number of charges of static electricity after 10 min of pumping (voltage 7 kv)
Fuel JP-5 without purification	$1{,}8 \times 10^{-12}$	40
Percolation purification with silica gel	$0{,}005 \times 10^{-12}$	0
Contact purification by clay	$0{,}009 \times 10^{-12}$	0
Hydroforming	$0{,}005 \times 10^{-12}$	5
Microfiltration	$0{,}013 \times 10^{-12}$	19

Influence of water and air bubbles. It was determined that in the presence in fuel of dissolved or dispersed water the quantity of charges of static electricity (with voltage on discharger of 7 kv) in him is significantly increased;

Dried aviation kerosene	60
Aviation kerosene with dissolved water	120
Aviation kerosene +0.5% finely dispersed water	150

Presence in fuel of air bubbles, as a rule, increases the tendency of fuel to formation of static electricity during pumping, which is clear form the following data about the quantity of charges of static electricity with voltage on discharger of 7 kv (speed of supply

air to fuel was equal to 500 ml./sec):

JP-5 without air 7
JP-5 with big air bubbles. 12
JP-5 with small air bubbles. 22

Influence of temperature. In most cases during heating of fuel within limits of temperatures from 10 to 40°C the tendency of fuel to formation of static electricity weakens (Table 74); however, in separate cases with such preheating the quantity of charges of static electricity is increased (JP-4(D)).

Table 74. Influence of Heating of Fuel on Formation of Static Electricity

Fuel	Number of charges of static electricity after 10 min of pumping at temperature		
	10°C	27°C	40°C
JP-4	3	2	0
JP-4	176	135	10
JP-4	125	118	13
JP-4	153	230	553

Table 75. Influence of High-Temperature Treatment of Fuel JP-4 on Formation in it of Static Electricity

Number of charges of static electricity after 10 min of pumping (voltage 7 kv)	
Up to determination of thermal stability of fuel	After determination of thermal stability (heating of fuel 150°C)
5	13
13	30
81	190

As is known, under the influence of high temperatures in fuel significant chemical changes occur; in some cases in it insoluble deposits are formed. At present in the United States the thermal stability of jet fuels is determined on coker apparatus, where stability

is estimated by the amount of deposits formed in the fuel. For instance, for fuel JP-4, tested for thermal stability on a coker apparatus, where it was subjected to heating to 150°C, the ability to form static electricity was significantly increased, which obviously is caused by formation in fuel of the smallest solid carbon particles (Table 75).

Analogous picture is observed with artificial addition to jet propellant of carbon substances; thus, even with the most insignificant addition of asphalt to fuel (0.005-0.0005%), the ability of fuel to form static electricity during pumping is significantly increased (Table 76).

Table 76. Influence of Carbon Substances (Asphalt) on Formation in Fuel of Static Electricity

Fuel	Specific electrical conductivity, $ohm^{-1} \cdot cm^{-1}$	Number of charges of static electricity
JP-5 without additions . .	0.011×10^{-12}	4
JP-5 + 0.005% asphalt. . .	0.5×10^{-12}	130
JP-5 + 005% asphalt, soluble in naphtha.	1.9×10^{-12}	131
JP-5 + 0.005% asphalt not soluble in fuel.	1.20×10^{-12}	112
Isooctane without additions	0.0008×10^{-12}	1
Isooctane + 0.0005% asphalt	0.0084×10^{-12}	2

As can be seen from Table 76, deposit insoluble in fuel more strongly increases the tendency of fuel to formation of static electricity.

Influence of oxidation of fuel during storage. During oxidation of fuel during its storage, accompanied by increase of content of potential resins, the ability of fuel to form static electricity during pumping is strongly increased (Table 77).

As was already shown above, all light oil products in pure form have specific electrical conductivity below 10^{-12} and under certain

conditions possess ability to form charge of static electricity. Experiments established that with electrical conductivity of fuels higher than 10^{-11} the danger of formation of static electricity during operations with fuel sharply decreases. On this very phenomenon the method of struggle with formation of charges of static electricity in fuel is mainly based — addition to it of special additives, increasing the electrical conductivity of fuel.

Table 77. Influence of Oxidation of Fuel on its Abiliy to form Static Electricity During Pumping (Fuel was kept in Barrel with Capacity of 200 Liters 17°C)

Duration of storage, days	Content of potential resins in fuel, mg/100 ml.	Number of charges of static electricity
Until storage	0.8	21
9	2.4	54
20	6.2	131

Introduction into the fuel of insignificant amount of certain substances, for instance, acids, alkalis, and alkali salts, permits significantly to increase the electrical conductivity of fuels. The biggest effect is given by additives possessing high surface activity in order to cope with static electricity. "Royal Dutch Shell" petroleum firm during storing operations began experimentally to introduce into fuel additive "Sa-aerosol OT." However this method now is in the stage of laboratory tests.

Due to specific conditions the formation of static electricity in fuel during work on fuel storage tanks of airports and during fueling of aircraft is especially probable. Here the latest technology, high speed of pumping, fine filtration of fuels are used, i.e., favorable conditions are created for the appearance of large charge of static electricity.

For removal of danger of explosion and fire the firm British Petroleum Company, servicing civil aviation of England, recommends to observe the following rules during fueling of passenger aircraft.

1. Before fueling of aircraft or decantation of fuel from tanks of aircraft is started, it is necessary that aircraft and all servicing assemblies were well connected together and grounded.

2. During fueling of aircraft during passage of fuel through pipeline, flexible hose and fueling gun, static electricity appears. For removal of charge of static electricity it is necessary that flexible hose has all along its length a metallic spiral and that fuel-lead, hose and fueling gun are connected and grounded.

3. Cistern of refueling unit, pump, fuel gauge and fuel lead must be reliably connected by copper wires with landing gear, through which their grounding is done.

4. Flexible hoses and fueling guns before beginning of fueling must be reliably connected with filled aircraft with the help of special wires and plugs.

5. All compounds and contacts of refueling units, intended for removal of static electricity must daily be thoroughly checked before beginning of work.

6. On ~~flying field~~ in places of fueling of aircraft special points are necessary for grounding of aircraft, refueling unit on hoses and tractors. Grounding points must be arranged in such a manner that they are easily accessible, and their number should be sufficient.

7. All operations on fueling of aircraft or decantation of fuel from tanks of aircraft must be ceased during thunderstorm or during approach of thunderstorm to airport.

21. STORAGE OF JET FUELS AT AIRPORT STOREHOUSES

During prolonged storage of jet propellants in fuel storage tanks of airports, their physicochemical characteristics, can be significantly changed, as a result of which the quality of fuels will sharply worsen.

Main factors rendering influence on the quality of fuels during prolonged storage are: temperature of storage, presence in fuel of water, and airtightness of container during storage.

Prolonged storage of fuels in insufficiently hermetic container leads to heavier fractional composition and increase of density due to evaporation of light fractions. This is especially dangerous for fuels of light fractional composition (T-2). Prolonged storage at increased temperatures, especially in the presence of water, causes oxidation of fuels.

Depending on the depth and direction of oxidizing processes in fuel, tar deposits can be formed. Sometimes products of oxidation will be in dissolved state; in this case fuel can change its color.

Inasmuch as temperature conditions of storage render essential and sometimes also decisive influence on the change of quality of fuel, one should consider conditions of storage of jet propellants in underground and ground containers.

Storage of Jet Fuels In Ground Cisterns

During storage in gorund cisterns the temperature of jet propellant practically will follow change of temperature of external air, but with certain lag due to the low coefficient of thermal conductivity of jet propellants. The greater the volume of fuel poured into the cistern, the greater this lag will be.

Table 78. Influence of Color of Cistern on Temperature and Loss of Fuel (Temperature of Air +30°C)

Color of cistern	Temperature of fuel, °C	Annual losses of fuel from evaporation, wt %
Aluminum. . . .	11.5	0.83
Gray.	14.6	1.03
Red	22.0	1.14
Black	30.0	1.27

During storage in gorund containers the temperature of jet propellant in one year can be changed from 40 to -60°C in northern regions and from 40 to -40°C in central regions of Soviet Union.

Strong cooling of jet propellant during storage practically does not cause any irreversible changes of qualitative characteristics of jet fuel, since during heating all of its initial properties are completely resorted (viscosity, density etc).

Prolonged storage of fuel high temperatures not only is undesirable, but also dangerous. During heating vapor pressure is increased, volatility is sharply increased and losses of fuel from evaporation increase.

Intensity of heating of fuel during storage in ground containers depends on color of cistern. Light colored or aluminum painted cisterns, are heated more weakly, thanks to which the loss of fuel from evaporation will be less (Table 78).

Storage of Jet Propellants in Underground Cisterns

Prolonged storage of jet propellants of all grades in underground containers is preferable, since with this fuel is heated less, twenty-four hour oscillations of fuel temperatures are insignificant and seasonal oscillations of temperatures are also relatively small.

In Table 79 are listed temperatures of ground at different depth in winter in central strip of Soviet Union, on which the temperature of fuel depends to a significant degree.

Table 79. Temperature Conditions in Underground Reservoirs [40]

Depth of bedding of ground	Average difference of temperatures of ground in winter and in the summer, °C		Average winter temperatures of ground at different depth, °C	
	Natural cover	Bare surface	Natural cover	Bare surface
0	50	50	−16	−1[illegible]
0.5	18	25	−3	−7
1.0	13.5	17.5	−0.5	−2.8
1.5	10	13	1	−0.6
2.0	8	10	1.9	0.9
2.5	6	7	2.0	1.7
3.0	4.4	4.6	2.0	2.1

Due to smaller heating of fuel in underground cistern, oxidation and resinification of fuels during storage in underground cisterns will be significantly less. Absence of sharp twenty-four hour oscillations of temperatures of fuel significantly decreases its losses from evaporation due to breathing of cisterns.

Conditions of Storage of Jet Fuels

Jet propellants can be kept in fuel storage tnaks of airports in ground, underground or semi-underground reservoirs.

For removal of errors and confusion of grades of fuel it is

necessary that for each grade of fuel permanent reservoirs were singled out, having independent system of pipelines and pumps for decantation and issuing of fuel for fueling of aircraft.

For removal of losses of fuel from evaporation, and also for protection of fuels from entry into them of contaminations, dust or water it is necessary that hatches of reservoirs and cisterns, and also covers on decantation pumping hatches are hermetically closed.

During storage of fuels in ground reservoirs it is recommended to color them in light tones, in order to lower heating from solar rays and thereby to decrease losses of fuel from evaporation.

Safety valves of reservoirs and cisterns must be in good working order.

Fuel T-2, having lightened fractional composition and sufficiently high vapor pressure is more volatile than fuel T-1 and TS-1.

During storage of fuel in reservoirs and cisterns, gradual accumulation of free water on the bottom of container is observed. It is required regularly to remove accumulated water from reservoirs and cisterns, in order to eliminate entry of water and fuel with water content into tanks of aircraft during their fueling.

For protection of fuel from contamination by mechanical impurities and tarry substances it is necessary regularly, not less than two times a year, (in spring and in autumn) to clean reservoirs and cisterns. During cleaning of reservoirs it is necessary to observe all rules of safety engineering and fire-fighting measures.

Evaporation of Jet Propellants From Surface

During prolonged storage of jet propellants in unhermetic reservoirs certain losses of fuels owing to their evaporation are observed.

Comparative estimate of volatility of different grades of jet propellants during storage in open containers of equal volume and with equal magnitude of evaporated surface is shown in Table 80.

Table 80. Losses of Fuel from Evaporation During Storage

Fuel	Average vapor pressure at 38°C, mm. Hg	Losses from evaporation according to Budarova, %	
		GOST 6369-52	Comparative losses
Aviation gasoline	350	1.40	100
Fuel T-2.	80	0.12	10
TS-1	35	0.06	5
T-1.	25	0.04	4
Diesel Summer . .	5	0.0013	1

22. FUELING OF AIRCRAFT

Aviation fuels are contaminated by mechanical impurities mainly during their transport, pumping, decantation and storage.

Main types of mechanical impurities getting into aviation fuels are ferric oxide (cinder), sand, carbon and fibrous substance.

Fuel is contaminated chiefly because of insufficient airtightness of cisterns and reservoirs, their bad cleaning before fueling, and also due to absence in the majority of cases in cisterns, reservoirs and pipelines of anticorrosive coverings, which causes entry into fuel of high quantity of cinder. Therefore with progress from oil refining factory to consumer the quantity of mechanical impurities in fuel is increased. Thus, content of mechanical impurities in fuels arriving in railroad cisterns reaches 20 mg/liter, while for fueling of aircraft it is permitted to issue fuel with content of mechanical impurities not more than 1 mg/liter.

For purification of fuels and removal from them of mechanical impurities, fuel before delivery for fueling of aircraft is allowed to settle and then filter.

In latest types of aircraft with gas turbine engines used in transport and military aviation of foreign countries, the volume of fuel tanks oscillates from 20,000 to 90,000 liters (Table 81).

Consequently, for complete fueling of one aircraft in some cases two railroad cisterns of fuel are required.

At present aircraft are fueled by the following two methods.

1. With the help of mobile refueling units of great capacity (up to 45,000 liters). On large refueling units powerful fuel are fixed, thanks to which speed of fueling can reach 4700 liters/min; consequently, for fueling of aircraft not more than 15-20 min will be required.

2. In recent years abroad a system of fuel feed directly on flying field by pipeline has been more and more widely used. On flying field at fueling places of aircraft fueling columns (wells) are fixed. For each such well there can be several flexible hoses, with the help of which aircraft is filled simultaneously at several points.

Table 81. Volume of Fuel Tanks of Some Types of Foreign Aircraft [41]

Aircraft	Volume of fuel tanks, liters	Speed of fueling, liters/min	Quantity of fueling hatches on aircraft
Viscount-800...	8900	1810	2
Caravelle-210..	18650	1360	2
Bristol Britannia-310..	39100	1360	2
DeHavilland-Comet-4.....	40900	1810	2
Convair-880....	40950	4540	4
Boeing-707.....	89800	5690	4
Douglas DC-8...	82700	5320	4
Lockheed Electra	21000	1360	2

Typical diagram of centralized fueling of aircraft is the following. Reserve of fuel is kept at base storehouse, which can be placed at a significant distance from place of fueling of aircraft. This storehouse usually is connected with the nearest railroad station by pipeline or railroad branch.

From reservoirs of base storehouse fuel is taken away in distributing container through floating intake tube; on the way it passes through water separator and filter of fine purification (10μ).

Distributing container and all pipelines going from it to flying

field must have anticorrosive coverings. From distributing container fuel is taken away through floating intake tube, and on the way to the aircraft it passes a second time through water separator and filter of fine purification (5u).

Liquid intended for preventing crystal formation is measured out and ejected into flow of fuel during its pumping from base storehouse to distributing container of airport. Such a method of addition of liquid ensures its complete mixing with fuel.

In literature opinion is stated that this is the only method of solution of problem of simultaneous fueling of a large number of aircraft (especially transit) in big airports; the use of large quantity of heavy refueling units sometimes so blocks the flying field that normal work of airport is disturbed.

Duration and Speed of Fueling of Aircraft

Duration of fueling of aircraft actually is determined by capacity of fuel tanks of aircraft and speed of supply (pumping) of fuel.

1. Transit aircraft are refueled not more than 30 min.

2. For very large aircraft (Boeing 707 and others) duration of fueling not more than 45 minutes is allowed. Time, expended on decantation of residuum or complete emptying of tanks from fuel of preceding fueling, is not included in norms of duration of fueling. In literature [16] it is indicated that for removal of danger of fire, caused by charges of static electricity, speed of pumping of fuel through pipelines during fueling of aircraft should not exceed 0.9 m/sec. With higher speed of pumping of fuel the charge of static electricity sometimes grows so intensely that normal grounding of fueling assemblies for removal of electricity can be insufficient.

Settling of Fuels

Settling as a method of removal from fuel of main mass of big particles of mechanical impurities and emulsified water sufficiently

effectively and widely is used in operational conditions of all countries.

In transport aviation of England such an order is fixed that fuel is not issued for fueling of aircraft as long as it did not settle in stationary container. For settling of fuel in airport reservoirs the following norms of duration of settling are fixed:

1) for settling of aviation gasolines not less than 50 min for each meter of depth gasoline level in reservoir is required.

2) for settling of jet propellants of type of aviation kerosenes not less than 3 hr 20 min for each meter of depth of fuel level in reservoir is required.

There are indications [66] that mechanical impurities 10 μ in dimension are precipitated from aviation kerosene (ATK) at -25.5°C 4 times slower than 15.5°C.

Thus, in winter period of operation of jet propellants the duration of settling must be significantly increased.

Filtration of Fuels

For removal of contamination of fuels during their storage and pumping in airports recently abroad reservoirs and pipelines with different anticorrosive coverings, began very successfully to be used, ensuring simultaneously hermetic sealing of reservoirs.

For filtration of fuels special filters of fine purification of different construction are used. At present the following types of filters of fine purification are used; paper, metal-ceramic and net-like. The latter permit to remove from fuel all mechanical impurities with dimension more than 5 μ.

Filters of fine purification are established not only on refueling units, but also in fuel system of aircraft. This is done in order to

prevent entry of mechanical impurities into fuel flow-control assembly, into high-pressure hoses and into burners of gas-turbine engine.

In United States transport aviation it is considered necessary to purify fuel from mechanical impurities up to inflow of fuel into aircraft tanks. Filters established in the fuel system of aircraft are coarser than those through which fuel is filtered during fueling of aircraft. Thus, during fueling of DC-8 aircraft, fuel is filtered through microfilters, with the help of which from it all mechanical impurities with dimension more than 5 μ are removed, and in fuel system of DC-8 aircraft there are established filters of fine purification, on which impurities with dimension of 10 μ are removed.

With such a system of filtration the danger of plugging of filters of fine purification of aircraft by mechanical impurities.

On ability of fuel to pass through filters of fine purification many factors render influence.

Small quantities of tarry substances, which can be in standard jet propellants, usually defined as actual resins, practically do not clog filters. However, if in fuel free water is present, then tarry substances are associated with drops of water and can be deposited on filter, and also cause plugging of its pores. This occurs because products of oxidation of fuel (resins), being associated with drops of water, give them stickiness, by which is caused their cohesion with each other with formation of tar film on filter.

Thus, during filtration of strongly resinified fuels through filters of fine purification their contamination by tarry substances, sometimes is observed, and the permeable capacity of filter is lowered. This phenomenon is especially clearly mainfested during filtration through paper microfilters. Speed of clogging of filter and lowering

or ability of fuels to be filtered depend not only on quantity of impurities and insoluble substances, but also on their character. The ability of fuels to be filtered is lowered most strongly with the presence of sticky substances, able to be packed on surface of filter or to clog pores of filter.

Ability of fuels to be filtered worsens during their cooling below the temperature of turbidity due to crystallization of high-melting hydrocarbons.

If fuel has bad ability to be filtered because of the presence in it of insoluble substances, then entry into such a fuel of small amount of water strongly worsens the ability to be filtered.

Presence in fuel of dissolved (hygroscopic) water at plus temperatures does not render essential influence on ability of fuel to be filtered. During cooling of moistened fuel its ability to be filtered sharply worsens, due to separation from fuel of the smallest drops of water and formation of ice crystals stopped by filter. During filtration of fuel through microfilters the main mass of ice crystals can be removed from fuel. During filtration of fuel through linen filters, which ensure removal of impurities with a dimension up to 20 μ only an insignificant part of ice crystals can be removed from fuel.

In operational conditions before delivery for fueling of aircraft, fuel is checked for the presence in it of water and mechanical impurities. Purity of fuel is estimated visually in most cases without use of any apparatuses or reaction vessels.

Methods of Visual Appraisal of Purity of Fuel

In Soviet Union before delivery of fuel for fueling of aircraft it is recommended to remove sample of fuel of 100-250 ml. According

to the standard it is required that fuel poured into glass cylinder with a diameter of 40-55 mm, be transparent and that it does not contain extraneous impurities and water suspended or on bottom of cylinder. However such a method of appraisal of purity of fuel is not very perfect, inasmuch as fuel, istimated as absolutely pure, during analysis by the weight method can contain up to 10 mg/liter of mechanical impurities.

In England purity of aviation fuel, issued for fueling of aircraft is checked according to the method of visual appraisal of state of fuel-water interface. For this sample of fuel 80 ml is removed, and poured into glass cylinder, where 20 ml of pure distilled water is added. Then fuel is well agitated with water and is allowed to settle 2-5 min. When fuel and water are completely stratified, on fuel-water interface all mechanical impurities and undissolved tarry carbon substances contained in fuel will gather.

State of fuel-water interface is estimated according to the following four-point system;

Number of point	Visual estimate of fuel-water interface
1	Interface transparent and clean
1B	Several little bubbles, located on periphery of interface
2	Lace film with small quantity of particles of mechanical impurities on interface
3	Freely floating lace film or small foam on interface
4	Small lace film and (or) large foam on interface

For fueling of aircraft fuel, is permitted having point not below 1 or 1B.

Fueling of Aircraft In Air [42]

For increase of flying range of passenger and transport aircraft, and also increase of range of operation of combat aircraft, in certain cases fueling of aircraft in air is used.

In foreign press the following three systems of fueling of aircraft in air are described.

Use of ropes and flexible hose. According to this system tanker aircraft is attached alongside the aircraft to be filled, located somewhat above it. From aircraft to be filled a rope is released, having on the end a small brake parachute, and from the tanker aircraft a rope, on the end of which is secured a dragging load and a special lock. Then tanker aircraft shifts in lateral direction, intersecting course of aircraft to be filled. With this ropes of both machines are connected by lock and recovered by winch fixed on aircraft to be filled. From tanker aircraft flexible hose, is extended, on end of which is fuel indicator. Fuel indicator enters into contact with fuel intake hose, fixed on aircraft to be filled; further nitrogen is blown through the system and fuel feed starts. After termination of fueling the fuel intake hose is disconnected from fuel indicator and tanker aircraft goes off to the side. Rope of aircraft to be filled is extended a definite length to weak link, on which break occurs. After that hose of tanker is taken inside the aircraft.

Similar system is used for fueling B-29 and B-50 bombers in the United States Air Force; as tanker is used re-equipped aircraft B-29 (KB-29M).

Refueling by this system is possible only at flight speeds, not exceeding 360 km/hr.

Use of rigid telescopic pipe. With this system the tanker aircraft has fuel tanks, pumps and a rigid telescopic pipe with fuel indicator. Telescopic pipe is secured by means of an articulated joint to the lower part of fuselage. At the end of pipe there are external rudders for control. For refueling in air the aircraft to be filled

is attached from behind to tanker, somewhat below it. Operator of fueling equipment directs (with the help of external rudders) the fueling pipe to fuel intake hose of aircraft to be filled and advances its telescopic link. With this the fuel indicator is engaged with fuel intake hose. Then valve is opened and starts fuel feed. Upon completion of fueling the fuel indicator is disconnected.

System of refueling in air with the use of rigid telescopic pipe at present is accepted for arming of The United States Air Force. Corresponding equipment is fixed on KB-29P tanker aircraft.

Fueling in air by this system is possible at speeds up to 500 km/hr; fuel moves with speed up to 1900 liters/min.

Use of flexible hose and cone. On tanker aircraft winch is fixed, by means of which flexible hose is released, having on the end a cone with fuel indicator. Aircraft to be filled is attached from behind to tanker aircraft in such a way that its fuel intake hose enters into cone, and with the help of lock is linked with indicator. Then valve is opened and fuel starts to be pumped.

Before completion of fueling the valve is closed and aircraft to be filled starts to be reduced. With this the hose is stretched and, when tensile stress reaches a definite magnitude, the fuel intake hose, is unhitched from indicator.

One of the last MK-14 winches, with hose whose internal diameter is equal to 76 mm., is calculated for fueling at flight speed up to 480 km/hr.

23. GRADES OF JET FUELS OF SOVIET UNION

With all the variety of grades of propellants used in the Soviet Union and abroad, at present three types of fuels have been determined absolutely clearly:

1) aviation kerosenes, evaporating within limits of 140-280°C;

2) fuel of wide fractional composition with inclusion of gasoline, ligroin and kerosene fractions, evaporating within limits of 60-280°C.

3) fuels for supersonic flight speeds of heavier fractional composition with vapor pressure and high thermal stability.

Aviation kerosenes evaporating within limits of 140-280°C and having freezing point of 60°C are considered the best grades of jet propellant. Such fuels possess high volume heat of combustion, low pressure of saturated vapors, good viscosity characteristics and ensure normal work of engine under all conditions of operation and during flights at great altitudes.

Fuels of wide fractional composition have the essential deficiency that they possess increased volatility, and high pressure of saturated vapors. Due to this, during work on fuels of wide fractional composition certain difficulties arise, connected with their evaporation and "boiling" at great altitudes, however during flights at altitudes up to 10-12 km. the use of fuels of wide fractional composition, having

vapor pressure not higher than 100-150 mm Hg is completely acceptable.

Grades of Jet Fuels

In civil aviation of Soviet Union three grades of jet propellants are used; T-1, TS-1 and T-2, (GOST 10227-62):

1) Fuel T-1 — kerosene fraction, obtained by direct distillation from low-sulfur crudes;

2) Fuel TS-1 — lightened kerosene fraction, obtained by direct distillation from sulfurous crudes;

3) Fuel T-2 — wide gasoline-kerosene fraction, obtained by direct distillation of crudes.

Specifications of jet propellants are listed in Table 82.

For turboprop engines the same grade of jet propellants is used as for turbojet engines.

Starting Fuels

Starting of gas turbine engine at low temperatures of external air sometimes is connected with difficulty of ignition of stream of atomized fuel in flow of air, flowing through combustion chambers of engine.

From the point of view of perfection of carburetion and ease of ignition of mixture in combustion chamber of these motors, decisve influence is rendered by volatility of fuel, which is determined by its fractional composition and vapor pressure. All other conditions being equal, the lighter the fractional composition and the higher the pressure of fuel vapors, the greater the speed of evaporation of fuel.

Very strong influence on evaporation of fuel is rendered by degree of atomizing. The finer the atomization, the bigger the specific surface (in $cm^2/ml.$) of evaporation, the higher the speed of evaporation of fuel, and, consequently, the better the process of carburetion in

Table 82. State Standard for Jet Propellant for Civil Aviation of Soviet Union (GOST 10227-62)

Physicochemical indices	Fuel		
	T-1	TS-1	T-2
Density at 20°C, g/cm^3, not below	0.800	0.775	0.775
Fractional composition, °C			
start point	Not above 150	Not above 150	Not below 60
10% is distilled not above	175	165	145
50% " " "	225	195	195
90% " " "	270	230	250
98% " " "	280	250	280
Remainder and losses in sum, %, not more than	2	2	2
Kinematic viscosity, cs;			
at 20°C, not less than	1.5	1.25	1.05
" −40°C, not more than	16	8	6
Acidity, mg KOH/100 ml. of fuel, not more than	0.7	0.7	0.7
Flash point in closed crucible, °C, not below	30	28	—
Height of sootless flame, mm., not less than	20	25	25
Temperature of beginning of crystallization, °C, not above	−60	−60	−60
Iodine number, g of iodine/100 g of fuel, not more than	2.0	3.5	3.5
Content of aromatic hydrocarbons, %, not more than	20	22	22
Content of actual resins, mg/100 ml. of fuel, not more than	6	5	5
Content of sulfur, % not more than	0.10	0.25	0.25
Including mercaptan sulfur, %	—	0.005	0.005
Ash content of fuels, %, not more than	0.003	0.003	0.003
Lowest heat of combustion, kcal/kg, not less than	10250	10250	10300
Corrosion test of copper plate	Sustains		
Content:			
of mechanical impurities and water	Absent		
of water-soluble acids and alkalis	The same		
Thermal stability at 150°C for 4 hr, mg/100 ml. of fuel	Not standardized, but determination is obligatory		
Vapor pressure at 38°C, mm Hg, not more than	—	—	100

engine.

Influence of air temperature on ignition and starting of motor is connected also with evaporation of fuel. The higher the air temperature, the higher the speed of evaporation of fuel. With increase of temperature of air the speed of evaporation of fuel increases and process of carburetion is improved.

To ease starting of gas turbine engines of certain types, especially at low temperatures, special starting fuels are used; unethylated aviation gasolines in pure form or in mixture with basic jet propellant. For engines, fixed on TU-104, as starting fuel is used unethylated aviation gasoline B-70 (GOST 1012-54) with addition of 1% MK-8 oil or transformer oil.

24. GRADES AND SPECIFICATIONS OF JET FUELS OF FOREIGN COUNTRIES

At present only in the United States, England and Canada are there more than 15 specifications for different grades of jet propellants [16]. However in transport aviation of these countries practically are used two types of jet propellants with small changes, aviation kerosenes ATK and fuel of wide fractionaly composition JP-4.

Recently two clearly expressed tendencies were noted in the area of use of jet propellants in transport aviation of foreign countries:

1) use of jet propellants of type of aviation kerosense is being expanded and use of fuel of wide fractional composition JP-4 is being reduced.

2) use of aviation kerosenes having temperature of beginning crystallization of -40° is being reduced, owing to increase of consumption of aviation kerosenes having temperature of beginning of crystallization from -50 to -55°C.

In capitalistic countries high degree of unification of grades of jet propellants used both in transport, and also in military avaition has been achieved. Some differences in physicochenical indices of jet propellants of different countries are caused, obviously, not by specific requirements of engines of these countries, but by raw-material resources and technology of their production.

Jet Propellants of England

For turbojet and turboprop engines of military and civil aviation of England four grades of fuels are used; fuel ATK (avtour 40), ATK (avtour 50) and JP-5 – represent aviation kerosenes of direct distillation of crude fuel JP-4 of wide fractional composition – gasoline kerosene fraction.

Detailed specifications of jet propellants of England given in Table 83.

Table 83. Specifications for Jet Propellants of England

Indices	ATK (JP-1)	ATK	JP-5	JP-4
Number of specification.	DERD-2482	DERD-2494	DERD-2498	DERD-2486
Time of last revision of specification.	1/III 1957	16/III 1957	15/IX 1960	1/VIII 1959
Grade of fuel according to international nomenclature.	Avtour-40	Avtour-50	Avcat	Avtag
Viscosity at 0°C, cs, not more than.	6.0	6.0	6.15 (-34.4°C)	–
Fractional composition °C, not above:				
20% is distilled. . .	200	200	–	143
50% " . . .	–	–	–	–
90% " . . .	–	–	–	243
end point	300	300	288	–
remainder during distillation, %, not more than	2	2	1.5	1.5
losses during distillation, %, not more than.	1.5	1.5	1.5	1.5
Flash, point, °C not below.	38	38	60	–
Freezing point, °C not above.	–40	–50	–48	–60
Density at 15.5°C, g/cm^3				
not below	0.775	0.775	0.778	0.751
not above	0.825	0.825	0.845	0.802

Table 83. (continued)

Indices	ATK (JP-1)	ATK	JP-5	JP-4
Vapor pressure at 38°C, mm Hg.	–	–	–	100–160
Content of aromatic, %, not more than	20.0	20.0	25.0	25.0
Bromine number, not more than.	5	5	5	5
Content of olefins, %, not more than	5	5	5	5
Heat of combustion, kcal/kg, not less than.	10170	10170	10170	10[illegible]
Coefficient of caloricity, not below	4500	4500	4500	5250
Content, % not more than of sulfur.	0.20	0.20	0.40	0.4[illegible]
of mercaptan sulfur.	0.005	0.001	0.001	0.001
Actual resins, mg/100 ml not more than	3.0	3.0	7.0	7.
Tests for copper plate at 100°C.	1B	1B	1	1
Resins by accelerated method, mg/100 ml., not more than	6.0	6.0	14.0	14.[illegible]
State of interface, points.	1B	1B	–	–
Change of volume of fuel with addition of water, ml, ...	1	1	1	1
Smoking point mm., not less than	–	–	18	–
Coefficient of smoking and volatility, not less than.	–	–	–	54
Thermal stability: pressure drop after 5 hr. mm Hg, not more than	–	–	330	330
deposits in preheater not more than	–	–	3	3

Jet Propellants of France

In civil and military aviation of France two grades of propellants are basically used:

1) fuel Air-3405 – aviation kerosene of direct distillation; by its basic indices it is very close to English grade Avtour-40, Air – 3405

differs from jet propellants T-1 and TS-1, used in civil air fleet of USSR mainly by its freezing point.

Fuel Air-3407 represents a wide fraction and by its basic indices is close to fuel T-2. Distinctive feature of fuel Air-3407 is the fact that its vapor pressure is permitted up to 160 mm Hg.

Table 84. Specifications for Jet Propellants of France (Ministry of Defence of France)

Indices	ATK	JP-5	JP-4
Number of specification.	Air-3405	Air-3404	Air-3407
Time of last revision of specification	31/X 1951	30/XI 1956	31/X 1955
Grade of fuel according to international nomenclature	Avtour-40	Avcat	Avtag
Viscosity at −18°C, cs, not more than	6.0	16.5 (−34.4°C)	—
Fractional composition, °C, not above:			
20% is distilled.	200	—	143
50% "	—	—	180
90% "	—	—	243
end point	300	288	—
remainder during distillation, %, not more than.	2.0	1.5	1.5
losses during distillation, %, not more than	1.5	1.5	1.5
Flash point, °C, not below	40	60	—
Freezing point, °C, not above. . . .	−40	−40	−60
Density at 15°C, g/cm^3:			
not below	—	0.788	0.751
not above	—	0.845	0.802
Vapor pressure at 38°C, mm. Hg . . .	—	—	100–160
Content of aromatic, %, not more than	20	25	25
Bromine number, not more than. . . .	—	5	5
Content of sulfur, %, not more than.	0.20	0.40	0.005
Content of mercaptans, %, not more than	0.005	0.005	0.005
Doctor test.		Negative	
Lowest heat of combustion, kcal/kg, not below.	10150	10100	10200

Table 84. (continued)

Indices	ATK	JP-5	JP-4
Actual resins, mg/100 ml., not more than	6.0	7.0	7.0
Potential resins, mg/100 ml., not more than	—	14	14
Corrosion of copper plate at 100°C.	Light Darkening	1B	No. 1
Smoking point, mm., not less than	—	18	—
Coefficient of smoking and volatility, not less than	—	—	94
Change of volume of fuel during mixing with water, ml., not more than	2.0	1.0	1.0
Color according to Seybolt, not below	+14	—	—

Detailed specifications for French jet propellants are given in Table 84.

Jet Propellants of the United States, Used in Military Aviation

In military aviation of the United States fuels JP-3, JP-4, and JP-5 are used. Fuel JP-3 represents gasoline of heavier composition; at present it practically is not used; fuel JP-4 is a fraction of wide fractional composition of direct distillation; it is used sufficiently widely in military aviation; fuel JP-5 represents aviation kerosene of heavier fractional composition with very high flash point. This fuel is used chiefly in naval aviation based on naval vessels.

Detailed specifications of the indicated grades of jet propellants are given in Table 85.

Table 85. Specifications for Jet Propellants of the United States MIL-J-5624E

Indices	JP-3	JP-4	JP-5
Time of last revision of specification	23/III 1960	23/III 1960	23/III 1960

Table 85. (continued)

Indices	JP-3	JP-4	JP-5
Viscosity at -34.4°C, cs., not more than	—	—	16.5
Fractional composition, °C:			
start point, not below	—	—	—
10% is distilled, not above	—	—	204
50% " "	177	188	—
20% " "	115	143	—
90% " "	243	243	—
end point, not above	—	—	288
remainder during distillation, %, not more than	1.5	1.5	1.5
losses during distillation, %, not more than	1.5	1.5	1.5
Flash point, °C, not below	—	—	60
Freezing point, °C, not above	—60	—60	—48
Density, g/cm^3:			
not below	0.739	0.751	0.788
not above	0.780	0.802	0.845
Vapor pressure at 38°C, mm Hg	250—360	100—160	—
Content, %, not more than:			
aromatic	25.0	25.0	25.0
olefins	5.0	5.0	5.0
sulfur	0.40	0.40	0.40
mercaptans	0.005	0.001	0.001
Heat of combustion, kcal/kg, not less than	10220	10220	10170
Coefficient of caloricity, not less than	5250	5250	4500
Actual resins, mg/100 ml., not more than	7	7	7
General content of potential resins (16 hr), mg/100 ml., not more than	14	14	14
Corrosion of copper plate at 100°C	No. 1	No. 1	No. 1
Coefficient of smoking and volatility, not less than	52	52	—
Smoking point, mm., not less than	—	—	19
Change of volume of fuel during mixing with water, ml., not more than	1	1	1
State of fuel — water interface.		Threads, lace and film are absent	
Thermal stability:			
change of pressure drop during test for 5 hr., mm Hg	—	330	330

Table 85. (continued)

Indices	JP-3	JP-4	JP-5
deposits in preheater. . . .	—	3	3
Addition of stabilizer against resinification, lbs./1000 bars. .	8.4	8.4	8.4
Addition of deactivators lbs./1000 bars.	2.0	2.0	2.0

Jet Propellants of the United States, Used in Civil Aviation

In civil aviation of the United States, jet propellants manufactured according to specification of ASTM (D-2) are used. According to this specification three grades of fuels are manufactured: grade A (Avtour-40), grade A-1 (Avtour-50), and grade B(JP-4).

Detailed specifications of these fuels are given in Table 86.

Table 86. Specification of ASTM of the United States for Jet Propellants (D-2 1959)

Indices	Grade		
	Type-A	Type-B	Type-A-1
Grade of fuel according to international nomenclature. . .	Avtour-40	Avtag (JP-4)	Avtour-50
Viscosity at −34.4°C, cs, not more than	15	—	15
Fractional composition, °C:			
10% is distilled, not above	204	—	204
20% " " " "	—	143	—
50% " " " "	232	183	232
90% " " " "	—	243	—
end point.	288	—	288
remainder during distillation, %, not more than . .	1.5	1.5	1.5
losses during distillation, %, not more than	1.5	1.5	1.5
Flash point, °C, not below. .	43	—	43
Freezing point, °C, not above	−40	−51	−50
Density, g/cm^3:			

Table 86. (continued)

Indices	Grade		
	Type-A	Type-B	Type-A-1
not below.	0.775	0.750	0.775
not above.	0.830	0.801	0.830
Vapor pressure at 38°C, mm Hg	—	160	—
Content, %, not more than:			
aromatic	20	20	20
olefins.	—	5	—
sulfur	0.3	0.3	0.3
mercaptans	0.003	0.003	0.003
Heat of combustion, kcal/kg, not less than	10220	10220	10220
Actual resins, mg/100 ml., not more than	7	7	7
Potential resins, mg/100 ml., not more than	14.0	14.0	14.0
General acidity, mg KOH/g of fuel.	0.10	—	0.10
Corrosion of copper plate after 3 hr at 50°C.	No. 1	No. 1	No. 1
Smoking points, mm , not less than.	20	—	20
Coefficient smoking and volatility not less than. . .	—	54	—
Change of volume of fuel during mixing with water, not more than	±2	±1	±2
Thermal stability:			
change of pressure drop after 5 hr, mm Hg	300	300	300
deposits in preheater, not not more than.	3	3	3

The largest engine-building firms of the United States have their own specifications for jet propellant Avtour-40, which are listed in Table 87.

Jet Propellants of Canada

In military and civil aviation of Canada two grades of jet propellants are used: Avtour-50 and JP-4. Detailed specifications of these fuels are given in Table 88.

Table 87. Specifications for Jet Propellants of Aviation Engine-Building Firms of The United States

Indices	"Pratt-Whitney"	"General Electric"	"Allison"
Grade of aviation fuel according to international nomenclature	Avtour-40	Avtour-40	Avtour-40
Viscosity at −30°C, cs, not more than	10	15 (−34°C)	15 (−34°C)
Fractional composition, °C, not above:			
10% is distilled	204	204	204
50% "	—	234	234
90% "	300	288	300
losses during distillation, %, not more than	1.5	1.5	1.5
remainder during distillation, %, not more than	1.5	1.5	1.5
Density, g/cm^3:			
not below	0.751	0.750	0.775
not above	0.840	0.840	0.830
Vapor pressure at 38°C, mm Hg.	160	160	—
Content, %, not more than:			
aromatic	20	25	20
olefins	—	5	—
sulfur	0.30	0.30	0.30
mercaptans	0.005	0.003	0.003
Heat of combustion, kcal/kg, not less than	10220	10220	10220
Actual resins, mg/100 ml., not more than	7	7	7
Potnetial resins (16 hr), mg/100 ml, not more than	14	14	14
Corrosion of copper plate 100° C	No. 1	No. 1	No. 1
Smoking point, mm., not less than	25	20	20
Coefficient of smoking and volatility, not below	54	—	—
Change of volume of fuel during mixing with water, ml., not more than	2	1	2
Thermal stability:			
change of pressure drop after 5 hr of tests, mm Hg, not more than	300	200	—
deposit in preheater, not more than	3	3	—

Table 88. Specification for Jet Propellants of Canada

Indices	Grade	
	I	II
Number of specification	3-dr-23s	3-dr-22s
Time of last revision of specification	10/VI 1959	20/III 1959
Grade of fuel according to international nomenclature	Avtour-50	Avtag (JP-4)
Viscosity at −40°C, cs, not more than	15	–
Fractional composition, °C:		
20% is distilled not above	200	143
50% " "	–	187
90% " "	–	243
end point " "	300	–
remainder during distillation, %, not more than	2.0	1.5
losses during distillation, %, not more than	1.5	1.5
Flash point, °C, not below	39.4	–
Freezing point, °C, not above	−48	−60
Density at 15.5°C, g/cm^3	–	0.751 0.802
Vapor pressure at 38°C, mm Hg	–	100–160
Content, %, not more than:		
aromatic	22	25
olefins	–	5
sulfur	0.20	0.40
mercaptans	–	0.001
Heat of combustion, kcal/kg, not less than	10170	10220
Coefficient of caloricity, not below	4500	5250
Actual resins, mg/100 ml, not more than	7	7
Resins by accelerated method, mg/100 ml., not more than	–	14
General acidity, mg KOH per 1 g of fuel, not more than	0.1	–
Tests for copper plate at 100°C	No. 1	No. 1
Coefficient of smoking and volatility, not less than	–	52
Change of volume of fuel during mixing with water, ml., not more than	1.0	1.0
Color according to Seybol, not below	+12	–

Company Specifications for Jet Fuels

Petroleum firm Shell Oil, supplying international air lines of capitalistic countries in Europe, Asia and Africa with jet propellants

offers three grades of fuels: Avtour-650, Avcat (JP-5) and Avtag (JP-4).

Company specifications of these fuels are given in Table 89.

Table 89. Quality of Jet Propellants Supplied to International Air Lines by Petroleum Firm "Shell Oil" (December, 1960)

Indices	Grade of fuel		
	Avtour-650 (ATK)	Avtag (JP-4)	Avcat (JP-5)
Freezing point, °C, not above. . . .	-56	-60	-47
Coefficient of caloricity, not below	6725	6980	6660
Actual resins, mg/100 ml., not more than	1.0	1.0	1.0
Resins by accelerated method, mg/100 ml., not more than	-	2.0	2.6
Content of aromatic, %, not more than	15	14	17
Change of volume of fuel during mixing with water, ml., not more than .	1.0	1.0	0
Density at 15.5°C, g/cm^3.	0.793	0.756	0.800

Rocket Fuels of Foreign Countries

In rocket technology of foreign countries as combustible component kerosene fractions obtained by method of direct distillation of crude, are widely used. According to the main physicochemical indices rocket fuels, manufactured according to specifications DERD-2495 and MIL-R-25576B are very close to jet fuel JP-5. Rocket fuel according to specification MIL-F-25558B has significantly heavier fractional composition and correspondingly higher density and viscosity.

Characteristic peculiarity of all grades of rocket fuels is very low content of aromatic and unsaturated hydrocarbons is permitted not more than 5%, of unsaturated hydrocarbons not more than 1%. For removal of these hydrocarbons from kerosene fraction, obviously, special methods of purification are used.

Complete specifications for rocket fuels of England and the United States are given in Table 90.

Table 90. Military Specifications for Rocket Fuels of England and the United States

Indices	MIL 25576B	MIL 25558B	DERD 2495
Grade of fuel		Kerosene	
Time of revision of specification	23/I 1959	23/X 1957	1/V 1960
Viscosity at −34°C, cs. not more than	16.5	60.0	6.0 (−18°C)
Fractional composition, °C:			
start point, not below	185	221	–
10% is distilled, not below	185	226	170
90% " not above	210	249	200
end point, not above	274	316	270
losses during distillation, %, not more than	1.5	1.0	1.5
remainder during distillation, %, °C, not more than	1.5	1.0	1.5
Flash point, °C not below	43	88	43
Freezing point, °C, not above	−40	−40	−40
Density, g/cm³:			
not below	0.801	0.842	0.778
not above	0.815	0.863	0.786
Content, %, not more than:			
aromatic	5	5	5
olefins	1	1	1
sulfur	0.05	0.07	0.05
mercaptans	0.005	0.001	0
Heat of combustion, kcal/kg, not below	10280	10280	10300
Actual resins, mg/100 ml., not more than	7.0	7.0	3.0
Potential resins, mg/100 ml., not more than	14	14	6
Corrosion of copper plate at 100°C	No. 1	No. 1	No. 1
Smoking point, mm., not below	25	20	35
Thermal stability:			
change of pressure after 5 hr, mm Hg	–	625	325
deposit in preheater, not more than	–	2	2
Change of volume of fuel during mixing with water, ml., not more than	1.0	1.0	1.0

25. QUALITY OF COMMERCIAL GRADES OF JET FUELS OF FOREIGN COUNTRIES

In 1962 the English petroleum company British Petroleum, which jointly with petroleum company Shell Oil supplies almost all airports and international air lines of capitalistic countries with aviation fuels, published list of airports [43] of 60 countries with indication of grades of propellants available in airports for fueling of aircraft. Of 200 airports mentioned in this list, only in 25 airports of international air lines along with aviation kerosene ATK is tnere jet propellant JP-4. All the remaining airports have only aviation kerosene ATK of the type Avtour-50 (Aeroshell-650). In majority of 25 airports, where there is jet fuel JP-4, military aviation of the United States is based (7 airports of Norway, 4 airports of West Germany, 3 airports of Spain, etc). Thus, on international air lines of capitalistic countries is used chiefly jet propellant of the type of aviation kerosene ATK, having temperature of beginning of crystallization not higher than $-50^{\circ}C$.

Quality of Jet Propellants Used in Europe

Main grade of propellant used in civil aviation of European countries is aviation kerosene (ATK) of type Avtour-50, its temperature of beginning of crystallization is below $-50^{\circ}C$. Aviation kerosenes

Table 91. Physicochemical Properties and Operational Characteristics of Jet Propellants of West European Countries

Indices	England	Belgium	Italy	Denmark	Sweden	Sweden	Holland	France
Airport	London	Brussels	Rome	Copenhagen	Stockholm	Stockholm	Amsterdam	Orly
Grade of fuel	ATK	ATK	ATK	Avtour-60	ATK	JP-4	Avtour-65	ATK
Density at 20°C, g/cm³	0.7857	0.8353	0.7902	0.7858	0.7920	0.7510	0.7861	0.7811
Density, degrees API	49	38	46	48	47	57	48	50
Fractional composition, °C:								
start point	150	158	150	150	153	60	149	152
10% is distilled	161	173	174	175	168	91	166	166
90% is distilled	225	214	227	226	220	224	227	225
end point	242	230	247	245	248	245	248	248
remainder during distillation, %	1	1	1.5	1.5	1.2	1.5	1.2	1.3
losses during distillation, %	1	1	0.5	0.5	0.8	0.5	0.6	0.5
Flash in closed crucible, °C	55	47	45	55	56	-3	-44	44
Content of actual resins, mg/100 ml	0	2.0	2.4	0	0	1.0	2.8	2.6
Aniline point, °C	62	62	60	60	62	40	62	60
Coefficient of calorificity	7056	7056	6816	6720	6760	5920	6912	7000
Pressure of saturated vapors at 38°C, mm Hg	10	10	10	10	10	151	14	14
Viscosity, cs:								
at -20°C	1.51	1.56	1.62	1.51	1.59	1.0	1.48	1.38
at 0°C	2.34	2.34	2.46	2.28	2.29	1.29	2.33	2.13
at -40°C	7.15	7.64	8.70	7.52	8.01	2.93	6.90	6.95
Temperature of crystallization (freezing), °C	-57	-54	-51	-53	-54	-65	-62	-53
Content, %:								
sulfur	0.093	0.093	0.090	0.083	0.084	0.150	—	—
mercaptan sulfur	0.0001	0.0002	0.0003	0.0001	0.0006	0.0101	0.0001	0.0001
aromatic hydrocarbons	17	13	11	17	15	15	17	19
Iodine number, g of iodine/100 ml of fuel	0.1	0.4	0.2	0.1	0.5	0.5	0.2	0.1
Test for corrosion of copper plate	Withstands							
Content of unsaturated hydrocarbons, %	0	0.2	0.1	0	0.3	0.3	0	0
Lowest heat of combustion, kcal/kg	10,380	—	—	10,325	10,250	10,450	—	—
Elemental composition, %:								
hydrogen	14.20	—	—	14.00	14.03	14.47	—	—
carbon	85.80	—	—	86.00	85.91	85.50	—	—
Group chemical composition, %:								
naphthenic	34.20	—	—	—	—	—	—	—
paraffin	51.30	—	—	—	—	—	—	—
aromatic	14.50	—	—	—	—	—	—	—
Mineral acids and alkalis	Absent							

of type Avtour-40 and JP-5, having temperature of beginning of crystallization of -40°C, practically are not used at all. Jet propellant of wide fractional composition of type JP-4 in civil aviation of European countries is used very rarely.

Aircraft of Swedish airlines, flying in Japan through regions of Northern Arctic Ocean, use fuel JP-4, since this fuel has temperature of beginning of crystallization (freezing) of -60°C.

In Table 91 are given physicochemical properties and operational characteristics of jet propellants of seven European countries.

Quality of Jet Fuels, Used in Countries of Asia Africa and Australia

In a number of countries of Asia, Africa, and also in Australia and New Zealand in civil aviation jet propellant of type of aviation kerosene (Avtour-50), having temperature of beginning of crystallization below -50°C is used exclusively. Jet propellant of wide fractional composition JP-4 practically is not used in civil aviation. Physicochemical properties and operational characteristics of jet propellants used in a number of countries of Asia, Africa, and Australia, are given in Table 92.

Quality of Jet Fuels, Used in the United States, Canada and Iceland

In civil aviation of the United States and Canada two grades of propellants are used basically - aviation kerosene of type Avtour-50 and fuel of wide fractional composition. In particular, in Canada, on Canada-Japan air line, passing through region of North Pole, having fuel JP-4 is used, having temperature of beginning of crystallization of -60°C.

Jet propellants of type Avtour-50 of production of factories of

Table 92. Physicochemical Properties and Operational Characteristics of Jet Propellants of Countries of Asia, Africa and Australia

Indices	Burma	Egypt	Madagascar	Iraq	Indonesia	Australia	India	Australia	New Zealand
Grade of fuel	ATP-650	ATK	ATK	Avtour-650	Aeroshell-650	Aeroshell-650	ATP-650	Aeroshell-650	Aeroshell-650
Density, degrees API at 20°C	45.1	52.6	50.0	48.5	48.0	48.9	49.2	49.0	48.9
Density, at 20°C, g/cm^3	0.8012	0.7884	0.7800	0.8244	0.7885	0.7842	0.7834	0.7842	0.7844
Fractional composition, °C:									
start point	162	146	148	145	159	156	156	158	155
10% is distilled	174	160	164	166	170	168	168	171	169
50% is distilled	192	189	174	186	189	188	188	188	190
90% is distilled	220	221	202	218	220	220	225	215	225
98% is distilled	236	245	223	238	240	238	244	233	240
remainder and losses, %	2	2	2	2	2	2	2	2	2
Viscosity, cs:									
at 20°C	1.64	1.58	1.35	1.68	1.69	1.63	1.51	1.52	1.57
at 0°C	2.32	2.30	1.96	2.19	2.61	2.33	2.25	2.27	2.34
at -40°C	8.79	7.24	5.85	7.02	8.84	8.48	7.82	7.79	8.03
Flash point, °C	50	48	—	40	50	44	48	45	44
Temperature of beginning of crystallization, °C	-49	-50	-52	-54	-50	-48	-50	-50	-50
Acidity, mg KOH/100 g	0.16	0.12	0.14	0.12	0.10	0.16	0.19	0.10	0.10
Actual resins, mg/100 ml	2.4	1.0	1.4	1.0	1.5	2.4	1.0	1.2	3.8
Iodine number, mg of iodine/100 g	0.1	0.2	1.2	0.8	0.2	0.1	0.1	0.2	0.1
Content of sulfurated (aromatic) hydrocarbons, %	16	11	11	4	7	9	11	6	8
Vapor pressure at 38°C, mm Hg	7	7	9	8	20	8	10	7	10
Height of smokeless flame, mm	24	28	30	34	34	29	28	29	28
Coefficient of smoking and volatility	—	—	—	—	—	—	—	—	—
Aniline point, °C	57	62.5	61	64.5	67.0	62.5	62.0	62.5	62.0
Coefficient of calorificity	6075	5520	6410	6895	7340	7105	7005	7105	7050
Corrosion of copper plate	With tests and tests								
Purity of fuel in points	1	1	1	1	1	1	1	1	1

the United States and Canada in most cases have higher density, somewhat heavier fractional composition and higher viscosity than analogous grades of propellants, used in countries of Europe, Asia and Africa.

Physicochemical properties and operational characteristics of jet propellants, used in the United States, Canada and Iceland, are given in Table 93.

Table 93. Physicochemical Properties and Operational Characteristics of Jet Propellants, Used in the United States, Canada and Iceland

Indices	Canada	Iceland	The United States	
			I	II
Airport	Ottawa	Keflavih	New York	New York
Grade of fuel	ATK	Avtour-50	JP-4	Avtour-50
Density, degrees API	42	45	52.6	41
Density, at 20°C, g/cm^3	0.815	0.801	0.7684	0.820
Fractional composition, °C:				
start point	170	153	82	160
10% is distilled	189	177	98	184
50% "	214	200	139	206
90% "	243	238	201	240
98% "	261	260	245	254
remainder and losses, %	1.5	1.5	2	1.5
Viscosity, cs:				
at 20°C	2.20	1.81	0.98	2.10
" 0°C	3.46	2.76	1.30	3.40
" −40°C	15.02	10.50	2.94	15.20
Flash point, °C	57	46	—	44
Temperature of beginning of crystallization, °C	−52	−55	−60	−52
Acidity, mg KOH/100 g	0.3	0.2	0.12	0.2
Actual resins, mg/100 ml	1	1	7	2
Iodine number, mg of iodine/100 g	0.9	1.0	0.2	0.6
Content of aromatic, %	6	6	25	13
Vapor pressure, mm Hg	7	6	120	5
Height of sootless flame, mm	27	28	23	28
Coefficient of smoking and volatility	—	—	62	—

Table 93. (continued)

Indices	Canada	Iceland	The United States	
			I	II
Aniline point, °C.	62	61	40.5	62
Coefficient of caloricity	6006	6300	5520	5940
Corrosion of copper plate		Withstands		
Cleanness of fuel in points	1	1	1	1

Thermal Stability of Jet Fuels

Determination of thermal stability of jet propellants used in various countries of Europe showed that almost all fuels possess high stability and at a temperature of 150°C give very small deposit (Table 94).

Table 94. Thermal Stability of Jet Propellants (Method in Glass Apparatus with Agitator)[61]

Fuel and method of test	Thermal stability of fuels according to laboratory method at 150°C for 4 hr		
	Actual resins, mg/100 ml.	General deposit of fuel, mg/100 ml.	Acidity of fuel, mg KOH/100 ml.
English ATK:			
up to test.	0	0	0
test without bronze	6.8	2.7	2.18
test with VB-24	16.8	14.9	4.35
Italian ATK:			
to test	2.4	0	0
test without bronze	—	—	—
test with VB-24	15.2	16.9	5.65
Danish ATK:			
up to test.	0	0	0
test without bronze	4.4	6.2	2.28
test with VB-24	15.6	7.0	3.48
Swedish ATK:			
up to test.	0	0	0
test without bronze	7.0	10.2	3.78
test with VB-24	17.2	10.8	4.78
Swedish JP-4:			
up to test.	1.0	0	0
test without bronze	—	—	—

Table 94 (Continued)

Test and method of test	Thermal stability of fuels according to laboratory method at 150°C for 4 hr		
	Actual resins, mg/100 ml	General deposit of fuel, mg/100 ml	Acidity of fuel, KOH/100 ml
test with VB-24	15.2	16.9	5.65
Dutch ATK:			
test without bronze . . .	6.2	0.3	1.9
test with VB-24	13.2	0.3	2.3
French ATK:			
test without bronze . . .	2.4	0.1	0.2
test with VB-24	13.8	0.1	0.3

Corrosion Aggressiveness of Jet Fuels

Corrosion aggressiveness of jet propellants of foreign countries was determined by Ya. B. Chertkov [20] according to "KOS" method for 6 hr at 150°C (Table 95).

Table 95. Corrosion Aggressiveness of Jet Propellants

Country	Fuel	Content of sulfur, %	Content of mercapton sulfur, %	Corrosion of bronze VB-24 g/m^2
England.	ATK	0.093	0.0001	0.15
France	ATK	0.085	0.0001	0.15
Sweden	ATK	0.084	0.0006	0.35
Sweden	JP-4	0.150	0.0001	1.50
Holland.	ATK	0.090	0.0001	0.25
Denmark.	ATK	0.083	0.0001	0.25

26. AVIATION GASOLINES OF FOREIGN COUNTRIES

Wide use of gas turbine engines in military and transport aviation led to a significant reduction of use of aviation gasolines. In connection with this, recently in foreign countries the following changes occurred in the area of production of aviation gasolines:

1) production was ceased of aviation gasoline of grade 108/135, and of aircraft DC-6B, "Boeing-Stratocruiser," "Metropolitan-440" and others working on this grade of aviation gasoline were transferred to aviation gasoline of grade 115/145;

2) production was sharply reduced of aviation gasoline of grade 91/96, and aircraft working on this grade of aviation gasoline in many cases were transferred to aviation gasoline of grade 100/130.

In recent years of operation of aircraft with soft rubber tanks on aviation gasoline of grade 115/145, mass phenomenon of leaking of tanks was observed. Cause of disturbance of airtightness of rubber tanks turned out to be the chemical composition of gasoline. At present aviation gasoline of grade 115/145 is made almost completely of high-octane isoparaffin components without addition of aromatic; therefore it did not cause swelling of rubber necessary for creation of airtightness of tanks. Addition to gasoline 115/145 of around 5% of aromatic hydrocarbons ensures the necessary degree of swelling of

rubber, and leaking in tanks is ceased. On the basis of these investigations in new standard for aviation gasoline of grade 115/145 a minimum content of aromatic was established – not less than 5%.

On international air lines together with jet aircraft, aircraft with piston motors continue to work. Therefore it is important to know not only the physicochemical properties of aviation gasolines of different countries, but also to have exact information about what grade of aviation gasoline is used on different types of aircraft (Table 96).

Table 96. Use of Aviation Gasolines in Aircraft with Piston Engines

Aircraft	Engine	Aviation gasoline
Douglas DC-3	Pratt-Whitney R-1830	100/130
DC-4	Pratt-Whitney R-2000	100/130
DC-6	Pratt-Whitney R-2800	100/130
DC-6B	Pratt-Whitney R-4360	115/145
DC-7	Wright Compound R-3350	115/145
Constellation	Wright R-3350	100/130
Metropolitan-440 . . .	Pratt-Whitney R-4360	115/145
Super-Constellation. .	Wright-Compound R-3350	115/145
Boeing Stratocruiser .	Pratt-Whitney R-4360	115/145
Convair-340	Pratt-Whitney R-2800	100/130
IL-14	ASh-82T	B-95/130, B-100/130
LI-2	ASh-62IR	B-91/115, 91/96

In the majority of capitalistic countries aviation gasolines are produced according to specifications of England and the United States with insignificant changes in secondary constants.

On international airlines and in all capitalistic countries the following single scale of identification color of aviation gasolines by their grades is accepted:

73.	Colorless
80/87	Red
91/96	Blue
100/130	Green
115/145	Purple

In the Soviet Union, according to standard GOST 1012-54, the following scale of color of aviation gasolines by their grades is accepted:

B-70.	Colorless
B-91/115.	Green
B-95/130.	Yellow
B-100/130	Bright orange
BA-115/145.	Not standardized

In Tables 97-100 are listed specifications for aviation gasolines of England, the United States, France and Canada.

Table 97. Specifications for Aviation Gasolines of England (DERD-2485 from May 1, 1960)

Indices	Grade			
	73	91/96	100/130	115/145
Content of T.E.L., g/kg, not more than	0	2.7	2.7	2.7
Octane number				
aviation method	73	90	99	–
motor method	–	91	100	115*
Grade of rich mixture, not below	–	96	130	145
Heat of combustion, kcal/kg not below	10,300	10,300	10,300	10,500
Coefficient of caloricity, not below	7,500	7,500	7,500	9,000
Content of aromatic, %, not below	–	–	–	5
Fractional composition, °C, not above:				
10% distilled	75	75	75	75
40% distilled	75	75	75	75
50% distilled	105	105	105	105
90% distilled	135	135	135	135
end point	170	170	170	170
sum of temperatures of boiling away 10% + 50%, not below	135	135	135	135
sum of losses and residuum, %, not more than	3	3	3	3
Vapor pressure mm Hg:				
not below	270	270	270	270
not above	370	370	370	370
Content of sulfur, %, not more than	0.05	0.05	0.05	0.05
Content of actual resins, mg/100 ml., not more than	3	3	3	3
Freezing point, °C, not above	-60	-60	-60	-60
Change of volume during mixing with water, ml., not more than	2	2	2	2
Content of inhibitor, g/100 liters	2.4	2.4	2.4	2.4

*Grade on lean mixture.

Table 98. Specifications for Aviation Gasolines of the United States (MIL-G-5572c, revised June 30,1960)

Indices	Grade			
	80/87	91/96	100/130	115/145
Content of T.E.L., g/kg, not more than	0.3	2.7	2.7	2.7
Octane Number (motor method), not below	80	91	100	115
Grade of rich mixture, not below	87	96	130	145
Heat of combustion, kcal/kg, not below	10,400	10,400	10,400	10,500
Coefficient of caloricity, not below	7,500	7,500	7,500	10,000
Content of aromatic, %, not less than	—	—	—	5.0
Fractional composition, not above:				
10% distilled	75	75	75	75
40% distilled	75	75	75	75
50% distilled	105	105	105	105
90% distilled	135	135	135	135
end point	170	170	170	170
sum of temperatures of boiling away 10% + 50%, not below	135	135	135	135
losses during distillation, %, not more than	1.5	1.5	1.5	1.5
remainder during distillation, %, not more than	1.5	1.5	1.5	1.5
Reid vapor pressure at 30°C, mm Hg:				
not below	270	270	270	270
not above	370	370	370	370
Content of sulfur, %, not more than	0.05	0.05	0.05	0.05
Corrosion of copper plate, not above	No. 1	No. 1	No. 1	No. 1
Actual resins, mg/100 ml., not more than	3	3	3	3
Potential resins, after 16 hr, mg/100 ml., not more than	6	6	6	6
Freezing point, °C, not above	-60	-60	-60	-60

(Table 98 Cont'd)

Indices	Grade			
	80/87	91/96	100/130	115/145
Change of volume of fuel during mixing with water, ml., not more than.....	2	2	2	2
Addition of stabilizer against resinification, g/100 liters.	2.5	2.5	2.5	2.5

Table 99. Specifications for Aviation Gasolines of France (Air-3401-G from Dec. 31, 1957)

Indices	Grade			
	80/87	91/96	100/130	115/145
Content of T.E.L., ml/liter, not more than.....	0.13	1.2	1.2	1.2
Octane number:				
aviation method, not less than.....	80	91	100	115
motor method, not less than.....	80	90	—	—
Grade on rich mixture, not below.....	87	96	130	145
Heat of combustion, kcal/kg, not below.....	10,400	10,400	10,400	10,500
Fractional composition, °C:				
10% is distilled not above	75	75	75	75
40% is distilled not below	75	75	75	75
50% is distilled not above	105	105	105	105
90% is distilled not above	135	135	135	135
end point, not above.....	170	170	170	170
sum of temperature of boiling away 10% + 50% not below.....	135	135	135	135
losses + remainder, %, not more than.....	3	3	3	3
Reid vapor pressure, mm Hg:				
not below.....	270	270	270	270
not above.....	370	370	370	370
Content of sulfur, %, not more than.....	0.05	0.05	0.05	0.05
Corrosion of copper plate at 100°C, not more than.....	IB	IB	IB	IB
Actual resins, mg/100 ml., not more than.....	3	3	3	3
Potential resins, mg/100 ml., not more than.....	6	6	6	6
Freezing point, °C, not above.....	-60	-60	-60	-60
Change of volume of fuel during mixing with water, ml., not more than.....	2	2	2	2
Color of gasoline.....	Red	Blue	Green	Purple

Table 100. Specifications for Aviation Gasolines of Canada (3 - GP-25c, revised May 3, 1956)

Indices	Grade			
	80/87	91/96	100/130	115/145
Content of T.E.L., g/kg	0.3	2.7	2.7	2.7
Octane number:				
motor method, not below	80	90	99	—
aviation method, not below	—	91	100	115
Grade on rich mixture, not below	—	96	130	145
Heat of combustion, kcal/kg, not below	10,400	10,400	10,400	10,500
Coefficient of caloricity, not below	7,500	7,500	7,500	10,000
Fractional composition, °C:				
10% is distilled not above	75	75	75	75
40% is distilled not below	75	75	75	75
50% is distilled not above	105	105	105	105
90% is distilled not above	135	135	135	135
end point not above	170	170	170	170
sum of temperatures of boiling away 10% + 50%, not below	135	135	135	135
sum of losses and residuum, %, not more than	3	3	3	3
Vapor pressure at 38°C, mm Hg:				
not below	270	270	270	270
not above	370	370	370	370
Content of sulfur, %, not more than	0.05	0.05	0.05	0.05
Corrosion of copper plate at 100°C, not more than	No. 1	No. 1	No. 1	No. 1
Actual resins, mg/100 ml., not more than	3	3	3	3
Resins by accelerated method (16 hr), mg/100 ml., not more than	6	6	6	6
Freezing point, °C, not above	-60	-60	-60	-60
Change of volume of fuel during mixing with water ml., not more than	1	1	1	1
Color of gasoline	Red	Blue	Green	Purple

27. FUELS FOR SUPERSONIC FLIGHT SPEEDS

Speed of flight of civil transport aircraft with piston engines in rare cases exceeds 500 km/hr; altitude of flight of such aircraft rarely exceeds 5000 m. At the indicated flight speeds the phenomenon of aerodynamic heating of aircraft is so insignificant that it does not have practical value. In transport aircraft with turbojet engines, for instance, in aircraft TU-104, where cruising speeds amount to 800-1000 km/hr, noticeable aerodynamic heating of aircraft already is observed. In the literature [44] it is indicated that during test flights of "Comet 4" aircraft at flight speed of the order of 800 km/hr increase of temperature of wing surface of aircraft of 25°C was observed. In other works it is reported that at flight speed of 965 km/hr aerodynamic heating of aircraft reached 35°C, and at speed of 1280 km/hr – 63°C.

For supersonic flight speeds the following temperatures of heating of aircraft are listed [45]: at M = 2 up to 120°C and at M = 3 up to 300°C.

Possibility of heating of fuel system and fuel to high temperatures at supersonic flight speeds determines special requirements for fuels. Fuels intended for flights at supersonic speeds must possess high thermal stability and very low pressure of saturated vapors.

Pressure of Saturated Fuel Vapors

As was already indicated, with increase of temperature of fuel poured into tanks of aircraft, pressure of vapors is increased (see Table 44). If we assume that in tanks of aircraft was poured fuel T-1, having vapor pressure of 30 mm Hg, then during heating of the fuel in tanks of aircraft during flight to 150°C its vapor pressure will reach 2.2 atm (tech). If under such conditions in aircraft tanks fuel T-2 is poured, having pressure of saturated vapors of 100 mm Hg, then during heating of it to 150°C the vapor pressure will reach almost 3.5 atm (tech) (Fig. 30), and at 230°C – 13.5 atm (tech). With such high pressure of saturated vapors fuel will boil and be evaporated, which not only will lead to large losses, but also will disturb the work of the fuel system of the aircraft.

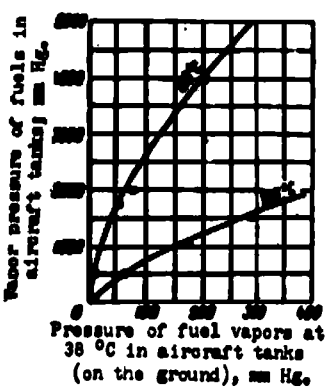


Fig. 30. Vapor pressure of jet propellants at 100 and 150°C depending on vapor pressure of these fuels at 38°C.

Table 101. Pressure of Saturated Fuel Vapors at High Temperatures

Temperature of fuel, °C	Pressure of saturated fuel vapors, kg/cm²	
	Gasoline B-100/130	Fuel ATK
100	1.6	0.1
315	25	5.6
370	36	11.2
430	47	15.4
450	64	28.0

Thus, for high-altitude supersonic flight speeds special fuel with very low vapor pressure is necessary.

Gasolines and jet propellants used at present in aviation during

heating give such a high pressure of saturated vapors that they turn out to be absolutely unfit for supersonic aviation (Table 101).

Thermal Stability of Jet Fuels

Recently considerable attention has been paid to the question of thermal stability of jet propellants used on aircraft with gas turbine engines.

The problem of thermal stability of gas turbine fuels appeared simultaneously with development of supersonic aviation. As is known, during flights at supersonic speed ($M > 1$) aerodynamic heating of aircraft is observed and, consequently, of its fuel system. The higher the flight speed, the greater the heating. In some cases the fuel in the fuel system can be heated to 120°C and higher [45]. Furthermore, in some types of aircraft the fuel is used for cooling of oil in the oil cooler, and in this case fuel can be additionally heated 25-40°C. In such conditions under the influence of high temperatures and atmospheric oxygen in the fuel deep chemical changes occur. With this the process of oxidation with formation of tarry substances and hard insoluble deposits proceeds.

The biggest difficulties in conditions of operation are caused by hard deposits, which deposited on the filters, can disturb fuel feed to the engine.

Thus, thermal stability of fuels for supersonic aviation is an important technical problem.

Type of Jet Fuels for Supersonic Flight Speeds

From what has been stated above it is clear that the chief characteristic of jet fuels is low pressure of saturated vapors and high thermal stability of fuels.

Production of jet fuel with low vapor pressure does not present special difficulties. Aviation kerosene of heavier fractional composition, which starts boiling around 200°C, fully corresponds to these requirements. One of the variants of heavier aviation kerosene is fuel JP-5, which now is widely used in the United States on subsonic and supersonic aircraft (M = 1.5) based on naval vessels. This fuel has low vapor pressure, but it possesses insufficient thermal stability; therefore at increased temperatures from it large quantities of insoluble deposits and tar-carbon substances are deposited in the fuel system of supersonic aircraft.

In recent years in the United States a new type of jet propellant JP-6 has been developed, which is characterized by high thermal stability during heating to 200°C.

Below is described the military specification of the United States for jet propellant JP-6 (MIL-F-25656) for supersonic aircraft:

Density at 15.5°C:	
not less than	0.780
not more than	0.840
Fractional distillation, °C:	
start point, not below	121
10% will be distilled, not above	177
50% will be distilled, not above	218
90% will be distilled, not above	260
sum of temperatures of boiling away 50% + start point, not below	316
losses during distillation, %, not more than	1.5
remainder during distillation, % not more than	1.5
Viscosity at -40°C, cs, not more than	15
Flash point, °C	not standardized
Freezing point, °C, not above	-54
Potential resins (16 hr), mg/100 ml, not more than	10
Content, %, not more than:	
aromatic hydrocarbons	25
olefin hydrocarbons	5
sulfer, general	0.4
mercaptan sulfer	0.001
Lowest heat of combustion, kcal/kg, not less than	10,220
Coefficient of caloricity, not less than	5,250
Smoking point, mm, not below	20

Thermal stability according to coker method:	
a) pressure drop on filter after 5 hr, mm Hg, not more than.	254
b) deposits in reheater	light brown
Addition of inhibitor, mg/liter, not more than. . . .	24
Addition of deactivator of metal, mg/liter, not more than	5.5

Below are described characteristics of fuels for supersonic aircraft [16 and 46].

Thermal stability of fuels according to method of ASTM-D-1660-59T should correspond to the following indices:

1) pressure drop on filter after 5 hr of injection of not more than 254 mm Hg;

2) deposits in preheater of apparatus are small and have light brown color.

Pressure of saturated vapors of fuels should be the following:

At 38°C, not more than . . . . . 5 mm Hg

At 150°C, not more than. . . . 500 mm Hg

At 260°C, not more than. . . . 3.5 kg/cm^2

Radiation number of fuel not less than 50; smoking of fuel not less than 20 mm.

28. INTERCHANGEABILITY OF JET FUELS

On international airlines at present, work chiefly aircraft with gas turbine engines and only on some intracontinental airlines are aircraft with piston motors used. Conditions of work of aircraft on international airlines are such that during one trip aircraft are forced to refuel in several countries. In connection with this jet propellants of different countries must be similar in basic physico-chemical indices, i.e., they must be interchangeable.

Interchangeable grades of jet propellants can be such for which fractional composition, viscosity, pressure of saturated vapors and temperature of beginning of crystallization (freezing) will be close.

From the point of view of interchangeability, jet propellants used on international airlines can be diveded into two groups: 1) jet propellants of type of aviation kerosenes, 2) jet propellants of wide fractional composition.

As a rule, it is not recommended (with the exception of special cases) for aircraft working on fuels of type of aviation kerosenes, to fill it up to full capacity or completely to refill it with fuel of wide fractional composition. It is not recommended also, although this is less dangerous, to refill or fill up to capacity aircraft working on fuel of wide fractional composition with fuel of type of

aviation kerosenes.

It is necessary to consider that inside the group of aviation kerosenes not all grades of jet fuels are completely interchangeable. On international airlines are used jet propellants of the type of aviation kerosenes with different freezing point (beginning of crystallization, in ^{o}C):

Avtour-40. . . . . -40
Avtour-50. . . . . -50
T-1, TS-1. . . . . -60

At present in practice of operation it is considered that jet fuels of the type of aviation kerosenes are interchangeable if the difference in temperatures of beginning of crystallization of fuels does not exceed $10^{o}C$ and if according to other indices they do not have large divergences.

In Table 102 are listed data about the interchangeability of jet propellants most frequently met on international airlines.

Table 102. Interchangeability of Propellants on International Airlines

Country	Aviation kerosenes		Fuels of wide fractional composition	
	Interchangeable grades	Specification	Interchangeable grades	Specification
Soviet Union	T-1 TS-1	Gost 10227-62	T-2	Gost 10227-62
England	Avtour-50 Avtour-40	DERD-2494 DERD-2482	JP-4	DERD-2486
The United States	Grade-A-1 (Avtour-50)	ASTM-D-3	JP-4	MIL-J-5624E
France	Avtour-40	Air-3405	JP-4	Air-3407
Canada	Avtour-50	3-GP-22e	JP-4	3-GP-22e

Note: Aviation gasoline Avtour-40, having temperature of beginning of crystallization of $-40^{o}C$ can be accepted for servicing of aircraft of Soviet Union only in exceptional cases.

Selection of Grade of Fuel for Civil Aviation

In military aviation of the United States and England fuel of wide fractional composition of type JP-4 is widely used. Once this grade of fuel began widely to be used in civil aviation, in the beginning in the United States and Canada, and then also in England and France. This to a significant degree was promoted by the fact that in the indicated countries in that period jet propellant of the type of aviation kerosene ATK had temperature of beginning of crystallization -40°C. However, in separate cases cooling of fuel in tanks of aircraft was observed during prolonged flights to -38°C; consequently, aviation kerosene having temperature of beginning of cystallization -40°C was dangerous to use. Therefore aviation kerosene ATK began frequently to be replaced by fuel JP-4.

In 1960 in England there appeared opponents of the use in civil aviation of fuel of wide fractional composition. As main argument the greater fire hazard of use of fuel JP-4 as compared with aviation kerosene, ATK was advanced.

For the solution of this question Ministry of Aviation of England created a special commission. As a result of two year work of this commission it was established [67] that during accidents of aircraft 1.5% of all who perish die from burns by burning fuel. The commission arrived at the conclusion that jet propellants of the type of aviation kerosenes ATK considered from the viewpoint of fire hazard are safer than fuel JP-4, and therefore aviation gasoline ATK is a more desirable type of jet propellant for civil aviation.

Comparative characteristics of inflammability of different grades of propellants, according to the commission, are listed in Table 103.

Table 103. Comparative Inflammability of Different Types of Jet Propellants in Conditions of Operation

Position of aircraft	Causes and conditions of appearance of fire	What grade of fuels are safer
Aircraft takes off, is in flight or accomplishes landing	1. Inflammation of fuel-air mixture in aircraft tanks. 2. Inflammation of foam formed on surface of fuel in aircraft tanks.	Aviation gasoline JP-4
Aircraft breaks down during landing (on ground)	During accident of aircraft fuel spills from tank.	
	1. Inflammation of spilled fuel.	Aviation gasoline
	2. Flame propagation on surface of spilled fuel.	Aviation gasoline
	3. Burning of spilled fuel.	Both grades of fuel are identical
	During accident of aircraft fuel will be sprayed and atomized with formation of mixture of air and small drops of fuel.	
	1. Inflammation of mixture of atomized fuel in air.	Both grades of fuel are identical
	2. Flame propagation in mixture of atomized fuel in air.	Both grades of fuel are identical
	3. Burning of atomized fuel in air.	The same
Servicing of aircraft with fuel on the ground	Formation of inflammable concentrations of fuel vapors in air	Aviation gasoline

From the given nine cases of possible appearance of fire, in four cases aviation kerosene is safer than fuel JP-4. In four cases both types with respect to fire hazard are identical and only in one case fuel JP-4 is safer than aviation kerosene (foaming).

At present for the majority of jet aircraft of civil aviation of foreign countries fuels of the type of aviation kerosene ATK are used, having a temperature of beginning of crystallization not higher than -50°C, instead of fuels used earlier, having temperature of beginning of crystallization of -40°C.

On international airlines during servicing of aircraft with aviation gasolines, jet fuels and oils, the volume of the filled product usually is measured. With this very frequently volume is scaled per weight units not according to density of the product measured in given conditions, but according to tables composed earlier of average scales of basic units of volume, which are used in given country (Table 104).

Table 104. Average Weights of Main Volume Units [47]

Product	Accepted average density, g/cm³	Average weight unit of volume, kg		
		liter	gallons USA	imperial gallons
Aviation gasolines	0,720	0,72	2,70	3,30
Aviation kerosenes	0,780	0,78	3,00	3,60
Oils for jet engines	0,940	0,94	3,50	4,30

29. QUALITY CONTROL OF JET FUELS

Selection of Samples of Fuel

Selection of samples of fuel for analysis to a significant degree promotes accuracy and correctness of appraisal of its quality. If sample of fuel was taken incorrectly, then with the most exact fulfillment of analysis it is possible to allow error in appraisal of quality and to reject good fuel or to allow unfit fuel in operation.

In order that there are no such errors, there exists a strictly determined order of selection of samples of fuel for analysis, which is standardized.

Selection from Railroad Cisterns

From biaxial cisterns one sample is taken from the middle of the cistern.

From tetraxial cisterns two samples are taken: one at a distance of 200 mm from the bottom of the cistern, the other at a distance of 200 mm from the upper fuel level. Then the average sample is made up by mixing equal amounts of the samples taken.

Selection from Horizontal and Vertical Reservoirs and Cisterns (underground and ground)

For appraisal of quality of fuels kept in vertical or horizontal

reservoirs with a diameter more than 2500 mm, samples are taken from three levels; the first is taken 200 mm below the fuel level, the second – from the middle of the height of poured fuel, and the third – from the level 100 mm below the lower rim of the fuel intake and distribution hose. To obtain the average sample the three taken samples of fuel are mixed together in definite ratios. The number of parts introduced into the average sample of fuel is listed below.

Level from which the fuel sample is taken	Vertical Reservoir	Horizontal reservoir with diameter more than 2500 mm
Upper	1	1
Middle.	3	6
Lower	1	1

From horizontal reservoirs with diameter up to 2500 mm, two samples of fuel are taken; one at a distance of 200 mm from the bottom of the cistern, and the second at a distance of 200 mm from the upper fuel level; then the average sample is made up by mixing equal quantities.

From horizontal reservoirs with a diameter more than 2500 mm, half-filled with fuel, the average sample is taken in the following order; 3 parts of sample taken from the middle of fuel level, and 1 part of the sample taken from level 100 mm below the lower rim of fuel intake and distribution hose.

Selection in Operational Conditions

From refueling units one sample is selected from the settling tank of the cistern.

From fuel tanks of aircraft sample is selected through overflow spigot

of the tank or in accordance with special instructions of the engineer.

Laboratory Quality Control of Jet Fuel

Laboratory control (analysis) is conducted in order to establish whether the quality of the given fuel corresponds to the existing standard.

According to the existing position, jet propellants are subjected to control analysis in laboratories of the airport in the following cases.

a. During receiving of fuel for airport storehouse, density of fuel, content of water and mechanical impurities (visually) are determined.

b. After overflow of fuel in airport container, fractional composition, kinematic viscosity at 20°C, flash point in closed crucible, content of actual resins, acid number, and content of water-soluble acids and alkalis are determined.

c. During storage of fuel in airport. If jet propellant for a prolonged time (more than 6 months) is kept in fuel storage vessel of the airport, then before delivery for fueling, the average sample of fuel is taken and density, fractional composition, kinematic viscosity at 20°C, flash point in closed crucible, content of actual resins, acid number, content of water-soluble acids and alkalis, and content of water and mechanical impurities are determined.

If analysis showed that quality of fuel corresponds to standard, it can be issued for fueling.

Airport Quality Control of Jet Fuels

The basic problem of airport control is fast visual check of quality of fuel directly before delivering it for fueling for the

purpose of preventing entry of mechanical impurities, water or fuel with water content in tanks of aircraft.

Quality control of fuel in this case consists of the fact that from refueling units a sample of fuel is selected in glass cylinder with a diameter of 40-55 mm and the fuel is examined in passing light. Fuel, proceeding to fueling, should be transparent and does not have to contain outside impurities or water suspended and settled on the bottom of the cylinder.

Parameters and Methods of Appraisal of Operational Characteristics of Jet Fuels

The problem of laboratory quality control of jet propellant is determination of physicochemical parameters of fuel and establishment of their conformity to standard.

Operational value of separate physicochemical parameters (see Table 80) and methods of their determination are briefly expounded below.

Density of fuel (GOST 3900-47). It is determined by areometer or hydrostatic scales. By density it is possible to distinguish with certain fraction of error one type of fuel from another. For instance, aviation gasolines have density of 0.700-0.750 g/cm^3; density of jet propellants T-2 is equal to 0.755-0.770 g/cm^3, TS-1 amounts to 0.775-0.800 g/cm^3, T-1 is within limits of 0.800-0.830 g/cm^3.

Fuel gauges (benzometers) used in operation determine volume units (liters); therefore for recount in weight units it is necessary to know the density of fuel. Amount by weight of fuel poured into tanks of aircraft is determined by multipling volume by density at the temperature of fueling.

Fractional composition (GOST 2177-59). With the help of fractional

distillation temperature of boiling away of separate fractions of fuel is determined on the basis of which the volatility of fuels is judged. In most cases the start and end points are determined and temperature of distillation of 10%, 50%, and 90% of fuel.

Pressure (elasticity) of saturated vapors of jet propellants (GOST 1756-52). It is determined in special instrument (bomb) at a temperature of 30°C and with a ratio of liquid phase to vapor 1:4; vapor pressure is expressed in millimeters of mercury. To a significant degree by vapor pressure are determined the high-altitude characteristics of jet propellants and their inflammability.

For jet propellants T-1 and TS-1 vapor pressure is not standardized, but practically at 38°C it does not exceed 50 mm Hg.

Viscosity of fuels (GOST 33-53). Kinematic viscosity of jet propellants is expressed in centistokes and in accordance with standard is determined at three temperatures; 20, 0 and -40°C. Dimension of viscosity is in cm^2/sec.

Viscosity of jet propellants is determined in capillary viscosimeters; determination reduces to measurement of time of outflow of fuel through calibrated capillary of definite volume of fuel.

In control laboratories of airports it is recommended to check the viscosity of jet propellants at 20°C.

Acidity of fuel (GOST 5985-59). Acidity is determined by quantity of milligrams of KOH which is required for neutralization of 100 ml of fuel. Acidity shows what amount of organic acids and other acid impurities enters into composition of fuel. Increased acidity is dangerous from the point of view of possibility of corrosion of fuel system of motor.

For all grades of jet propellants acidity is permitted not more than 0.7 mg KOH per 100 ml of fuel.

Flash point (in closed crucible) (GOST 6356-52). Flash point is the name for the temperature at which fuel vapors, heated in certain conditions, form with surrounding air a mixture which flashes during bringing up to it of open flame or during appearance of electrical spark.

By the flash point the homogeneity of jet propellants of the type of aviation kerosene is checked; furthermore, by it the degree of fire hazard of jet propellants is judged.

Flash point of fuel T-2 is not standardized, but practically occurs around -14°C.

Temperature of beginning of crystallization (GOST 5066-56). As temperature of beginning of crystallization of jet propellant is taken that temperature at which, in fuel, crystals are observed by the naked eye. For all grades of jet propellants the temperature of beginning of crystallization should be not higher than -60°C.

Jell point (GOST 1533-42). Jell point of fuels is the name for that temperature at which tested fuel, cooled in a test tube, in conditions of experiment congeals so much that with slope of test tube at an angle of 45° it remains motionless for 1 min.

Jell point of jet propellants is not standardized.

At jell point fuel cannot be pumped by a pump and also cannot be poured by gravity from railroad cistern. In this consists the practical value of index of jell point of fuels.

Jet propellants have jell point near -65°C.

Temperature of turbidity of jet propellants (GOST 5066-52). The method consists in cooling of a sample of jet propellant in standard conditions to a temperature at which turbidity of fuel sets in due to beginning of crystallization of high-melting paraffin or other high-melting hydrocarbons entering into composition of fuel.

In some cases turbidity of fuel sets in due to separation of dissolved water or formation of ice crystals. Temperature of turbidity of jet propellants T-1 and TS-1 usually occurs around -50°C; it is not standardized in the new standard.

Iodine number of fuel (GOST 2070-55). By magnitude of iodine number and by average molecular weight of tested fuel the content of unsaturated hydrocarbons of unsaturated hydrocarbons in fuel is determined.

Content of unsaturated hydrocarbons in fuel is calculated by the formula:

$$H = \frac{r \cdot M}{254},$$

where H is the content of unsaturated hydrocarbons in %; r is the iodine number of fuel; M is the average molecular weight of unsaturated hydrocarbons of fuel (by standard it is taken equal to 160), 254 is the molecular weight of iodine.

In some cases it is assumed that the quantity of unsaturated hydrocarbons in jet propellants amounts to 0.7 of its iodine number. If iodine number of jet propellant amounts to 3.5, then the content of unsaturated hydrocarbons in this fuel will be 2.45%.

Actual resins (GOST 1567-56). They comprise complicated products of oxidation, polymerization and condensation of hydrocarbons contained in jet propellants and formed during their evaporation under stream of air in test conditions.

Actual resins are determined by evaporation of 25 ml of fuel in standard glass beaker during heating in oil bath and during air blowing through fuel. Quantity of resins is calculated in milligrams per 100 ml of fuel.

Content of actual resins is an indirect index of intensity of formation of deposits of tarry substances in fuel system and scale forming ability of fuel; the more resins are contained in fuel, all the more probable is increased scale formation in combustion chamber of engine and on burners.

Content of sulfur (GOST 1771-48). Large content of sulfur in jet propellants is dangerous because it causes corrosion of assemblies of fuel system of the engine.

By specifications the content of sulfur in jet propellants is strictly limited and is checked (lamp method GOST 1771-48). Sulfur is determined with the help of burning of sample of fuel in a special lamp with subsequent collection of formed sulfurous anhydrite.

Content of mercaptan sulfur (GOST 6975-54). Mercaptans possess high corrosion aggressiveness, and their content in jet propellants TS-1 and T-2 is allowed not more than 0.005%.

Ash content of jet propellant (GOST 1461-52). Ash content of jet propellant is determined by burning weighed portion of jet propellant in platinum and porcelain crucible. Mineral remainder obtained with this is weighed and is expressed in percents of fuel, taken at burning.

Heightened ash content indicates contamination of fuel with inorganic substances.

Test for copper plate (GOST 6321-52). The method is used for determination of corrosion influence on copper plate of sulfur compounds or free sulfur contained in fuel, and consists of visual appraisal of change of color of copper plate immersed in tested fuel.

It is considered that fuel sustained test for copper plate, if when immersed in fuel for 3 hr at a temperature of 50°C it did not

change color and did not have dark brown or steel gray deposits or spots.

Content of water and mechanical impurities. Jet propellant poured into a glass cylinder with a diameter of 40-50 mm, outside impurities or water, should be transparent and should not contain suspended and settled on the bottom of the cylinder.

Quality Control of Aviation Fuels on Aviation Lines of England

In airports of airlines of England considerable attention is paid to questions of correct storage and quality control of aviation gasolines and jet propellants.

Fuel arriving at the airport in railroad or automobile cisterns up to overflow in container of the airport is checked according to the following indices; content of water, color, odor and general appearance. If water is detected in fuel, then until overflow of it in the container of airport water is completely absent.

During storage of fuels in airport containers water daily is checked and completely removed from reservoirs and cisterns.

Once in three months all fuels stored in airport reservoirs are subjected to control analysis according to the most important parameters (Table 105).

Table 105. Current Quality Control of Aviation Fuels, Taken in Airports of England [48]

Indices by which fuel is checked	Aviation kerosenes ATK DERD-2482 and DERD-2494	Fuel JP-4 DERD-2486	Aviation gasolines DERD-2485
Appearance (visually).....	+	+	+
Color (visually).....	+	+	+
Specific gravity.....	+	+	+
Fractional composition....	+	+	+
Content of actual resins..	+	+	+
Freezing point.....	+	0	0
Flash point.....	+	0	0
Content of mercaptan sulfur.....	0	+	0
Content of T.E.L.	0	0	+
Vapor pressure.....	0	+	0
Content of aromatics.....	0	+	0
Bromine number.....	0	+	0
Test for copper plate.....	+	+	0

Conditional designations: sign "+" -- analysis is made; sign "0" – analysis is not made.

LITERATURE

1. D. Howes and H. Rampton. The Journal of the Institute of Petroleum, 3, 306, 1949.

2. A. I. Baklagin. Journal of Applied Chemistry, 29, Issue 2, 1956.

3. Thermophysical properties of some aviation fuels in liquid and gaseous state. Oborongiz, 1961.

4. N. A. Ragozin. Jet propellants. Gostoptekhizdat, 1959.

5. Ye. R. Tereshchenko and M. Ye. Tararyshkin. Chemistry and technology of fuels and oils, No. 2, 1959.

6. G. W. Jones. Technical Report Wright Patterson Air Force Base, June, 1952.

7. W. P. Lakin. et. al. Fourth Annual Report. and Fundamental Studies of Combustion, November 30, 1948.

8. Basic consideration in the combustion of hydrocarbon fuels with air. USA, 1957.

9. R. Friedman and W. Johnston. Journal App. Physics, 21, 8, 1960.

10. Luftfahrttechnik, 9, 1957.

11. Recherche aeronautique, 67, 1958.

12. L. N. Khitrin and S. A. Goldenberg. Investigation of the process of propagation of turbulent flame front at high speeds of flow. Collection: Hydrodynamics and physics of combustion. Publishing House of the Academy of Sciences of the USSR, 1959.

13. M. G. Beard. SAE Journal, 67, 6, 74, 1959.

14. Flame luminosity. World Petroleum, 30, 13, 1959.

15. Luminometer number of aviation turbine fuel. ASTM, D-1660-59T.

16. R. G. Davies. Canadian Aeronautical Journal, 6, 8, 1960.

17. M. Jafface. Aviation Week, September 14, 1959.

18. Smoke point of jet fuels. ASTM, D-1322-58.

19. Motor fuels, oils and liquids, Vol. 1. Gostoptekhizdat, 1957.

20. Motor, jet, and rocket fuels. Gostoptekhizdat, 1962.

21. Z. A. Sablina and A. A. Gureyev. Additions to motor fuels. Gostoptekhizdat, 1959.

22. SAE Journal, 67, 5, 1957.

23. A. S. Eygenson and E. P. Toropova. Oil industry, No 2, 1948.

24. A. V. Kozhevnikov. Heavy liquid fuel for gas turbines. Gostoptekhizdat, 1962.

25. A. D. Fat'yanov. Boiler fuel. In book: Motor, jet, and rocket fuels, Chap. II. Gostoptekhizdat, 1962.

26. Ya. B. Chertkov, N. A. Ragozin, and N. I. Marinchenko. Chemistry and technology of fuels and oils, No. 4, 1961.

27. A. T. Polishuk and others. SAE Journal, 67, 6, 1959.

28. L. D. Derry, E. B. Evans, and B. A. Feulkner. The Journal Institute of Petroleum, 38, 343, 1952.

29. N. A. Ragozin. Reference book on aviation and automobile fuels. Gostoptekhizdat, 1947.

30. Choice of fuels for turbine engined airlines. Shell Aviation News, 225, March, 1959.

31. W. Kasten. Space aeronautics, 32, 3, 1959.

32. R. W. Stenzel. The refining engineer, 31, 1, 1959.

33. SAE Reprints, N 356B, 1961.

34. M. G. Godzhello and others. Inflammable and combustible liquids (Reference book), Edition MKKh, 1956.

35. N. A. Ragozin and A. F. Vorob'yev. Chemistry and technology of fuels and oils, No. 4, 1958.

36. M. G. Zabetakis, A. L. Furno, and A. M. Jones. The Industrial and Engineering Chemistry, 45, 10, 1954.

37. P. G. Demidov. Burning of substances and methods of slaking. Ministry of Municipal Services Press, 1955.

38. Dielectric Constant of Petroleum Products. ASTM, D-924-58.

39. N. A. Ragozin and N. F. Ronzhina. Chemistry and technology of fuels and oils, No. 6, 1959.

40. S. N. Aronov. Oil industry, No. 12, 1948.

41. Flugwelt februar., 38, 1959.

42. N. Nikolayev. Herald of air fleet, No. 12, 1954.

43. Fuelling facilities list of Air British Petroleum, Issue No. 2, April, 1962.

44. J. E. Walkery. The journal of the Royal Aeronautical Society, 56, 501, 1952.

45. C. R. Johnson. Industrial Eng. Chemistry, 46, 10, 1954.

46. Aircraft and missiles, VII, 1961.

47. Paul H. Wilkinson. Aircraft Engines of World London, 1960/61.

48. The Aircraft fuelling regulation and quality control of aviation fuel of British Aeroplan Airlines Issue. London, 1961.

49. M. J. Boegel and J. F. Wagnes. Relation of fuel properties to combustion cleanlines in gas turbine engine. SAE Annual meeting, Detroit, January 11-15, 1960.

50. Aviation week, 69, 23, 27, 1958.

51. V. Ya. Nikandrov. Transactions of main geophysical observatory, Issue 57 (119), 1956.

52. B. V. Kiryukhin and S. I. Pevzner. Transactions of main geophysical observatory, Issue 57 (119). Gidrometeoizdat, 1956.

53. L. G. Kachurin. Freezing of supercooled aerosols. Izd. AN SSSR, Geophysics Series, 2, 1951.

54. T. F. Borovik-Romanova. Transactions of Leningrad Institute of Experimental Meteorology, Issue I. Gidrometeoizdat, 1937.

55. A. D. Malkina and Ye. G. Zak. Transactions of Central Aerological Observatory, Issue 9. Gidrometeoizdat, 1952.

56. E. K. Bigg. Proc. Phys. Soc., B-66, 688, 1953.

57. Hugh Harvey. SAE Journal, June, 55, 1956.

58. B. P. Mullin. Report 90 NR, September, 1951.

59. M. P. Doss. Physical constants of the principal hydrocarbons. New York, 1948.

60. M. Ye. Reznikov. Aviation and rocket fuels and lubricating materials. Oborongiz, 1960.

61. K. K. Papok and N. A. Ragozin. Technical dictionary and reference book on fuel and oils. Gostoptekhizdat, 1963.

62. Thermophysical properties of some aviation fuels in liquid and gaseous state. Oborongiz, 1961.

63. Aviation week, 69, 23, 1958.

64. J. A. Hager. Aerospace Safety, April, 1961.

65. Chem. Eng., N 3, 1961.

66. G. T. Coker and R. G. Davies. SAE Journal, 67, 3, 1959.

67. The aeroplane and Commercial Aviat. news, N 3, 1962.